1984 GEOCHEMICAL STUDY OF
THE ACIDIC CONTAMINANT PLUME NEAR
THE NORDIC MAIN URANIUM-TAILINGS
IMPOUNDMENT, ELLIOT LAKE, ONTARIO

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1984 GEOCHEMICAL STUDY OF THE ACIDIC CONTAMINANT PLUME NEAR THE NORDIC MAIN URANIUM-TAILINGS IMPOUNDMENT, ELLIOT LAKE, ONTARIO

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SUMMARY

The objectives of this study were: 1) collect and evaluate 1984 aqueous geochemical data, 2) conduct detailed tests on the quality of 1984 data, and 3) compare 1983 and 1984 data with past years. The 1984 study followed the methods and approach used in the 1980-1982 studies (Morin, 1983). The 1983 study was conducted by the Elliot Lake Laboratory of CANMET and 1983 data were used with permission.

Field procedures used in this study were explained in detail. Methods and reported accuracies of methods used by laboratories in this study were also presented.

Data quality was evaluated through tests, such as ANOVA and Coefficient of Variation, on analytical results of replicate samples. Seven replicates each were collected from five piezometers. Replicates were divided into three sets and delivered to three laboratories for analysis of dissolved Fe, Ca, Mg, Na, K, Mn, Al, Cu, Co, Zn, Pb, Ni, SO_4, SiO_2, Cl, NH_3, NO_3, ^{226}Ra, Th, and U. Data quality tests indicate that precision and accuracy are variable. Choice of analytical methods and experience with analyzing similar water apparently have an effect on precision and accuracy.

The 1983 and 1984 profiles were compared to past profiles in order to evaluate plume outline, changes in concentrations, and plume movement. Plume outline has generally changed little, although 1984 concentrations were generally lower. Also, because the 1984 study was conducted in late Autumn rather than in Summer like previous years, the water table and rates of infiltration were higher, resulting in distortion of the plume at the water table. Plume movement is generally consistent with past years and simulations: 1 to 2 m/yr for the $Al(OH)_3$ and siderite sub-regions and about 10 m/yr for the calcite sub-region. However, Fe, SO_4, and a few other ions actually show retrograde movement of the concentration front in 1984. This movement is the result of incorrectly examining single-ion profiles for ions involved in precipitation-dissolution reactions. In these cases, log SI profiles should be examined for movement rather than single-ion profiles. Log SI profiles for siderite (in place of Fe) do show forward movement. The one-dimensional profiles

through the center of the plume have more uncertainties than realized in the past, but they can still be used to detect plume movement.

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1. INTRODUCTION

The Nordic Tailings Management Area, including the Nordic Main and Nordic West Arm tailings impoundments, is the best defined uranium-tailings site in Canada. Studies of this site began in 1973. From a hydrogeologic and geochemical viewpoint, the Nordic site has provided an abundance of data on water movement and on geochemical reactions affecting contaminant migration.

One aspect of the Nordic hydrogeologic study is the examination of subsurface contaminated seepage emanating from the base of the Nordic Main impoundment into the underlying/outlying sand aquifer (Figures 1 and 2). The study of this seepage was initiated in 1979 (Blair et al., 1980; Blair, 1981), was continued and expanded from 1980 through 1982 by Kevin Morin (Morin et al., 1982; Morin, 1983; Dubrovsky et al., in press; Morin and Cherry, in review), and was carried out in 1983 by Nand Dave and Tjoe Lim of the Elliot Lake Laboratory of CANMET and in 1984 by Morwijk Enterprises. The 1983 as well as 1984 data are examined here so that all hydrogeologic data on the seepage are contained in only two documents: this report and Appendix E of Morin (1983).

Morin (1983) identified four seepage area around the perimeter of the Nordic Main impoundment (Figure 1). Seepage Area A, also called the "plume area" in earlier documents, contains the most developed acidic groundwater plume at the Nordic site. Data collected on this plume were evaluated with data on one plume in Bancroft, Ontario, and on five sites in Wyoming, USA, in order to define the geochemical processes controlling and attenuating subsurface contaminant migration from uranium tailings. The geochemical processes were combined into a conceptual model of contaminant behavior, and this conceptual model was coded into a family of Fortran computer programs named ADNEUT (Morin, 1983; Cherry et al., 1984). The ADNEUT programs were used to simulate plume migration as observed since 1979, to define the probable past behavior of the plume, and to predict possible future scenarios of plume behavior.

Because such a detailed framework is already in existence for the plume in Seepage Area A, the 1984 study is limited to the following objectives: 1) collect and evaluate 1984 aqueous geochemical data, 2) conduct detailed tests on the quality of 1984 data, and 3) compare 1983 and 1984 data with past years. The quality of the data is evaluated through both interlaboratory comparisons among three laboratories and duplicates submitted to each laboratory. The laboratories were chosen primarily on the basis of experience with Area A waters. The interlaboratory comparisons indicate the degree of difficulty in accurately analyzing such high TDS water for major ions, minor ions, heavy metals, and radionuclides.

2. METHODOLOGY

This section presents the methods used for collecting data and water samples at the Nordic site and presents the methods for analyzing the water samples by the laboratories. Field methods are identical to those used by Morin (1983) to collect data and samples from 1980 to 1982 and closely follow the recommendations of Environment Canada (1983). Laboratory methods were not determined by Morwijk Enterprises; each laboratory was free to choose the analytical methods which it believed were appropriate.

2.1. Field Methods

The piezometers installed in the sand aquifer at the Nordic site are multi-level bundle piezometers (Cherry et al., 1983). Bundle piezometers consist of up to twelve individual piezometers, terminating at different depths, attached to a PVC center pipe for support. Each individual piezometer in a bundle consists of flexible 0.9 cm ID polyethylene tubing with a 10 cm long, 0.9 cm ID polyethylene screen at the base. The location of all bundles in the Nordic area are shown on Figure 3; bundle identification numbers are prefixed with an "M" and standpipe-piezometer nests are prefixed with a "T". Details of bundle installation and additional details of bundle construction can be found in Section 4.3 of Morin (1983).

Because the water levels in piezometers located in Seepage Area A are within three meters of the surface, water can be pumped directly from the piezometers by simply attaching a pump to the top of the pipe. In this way, the piezometers also represent dedicated sampling tubing, thereby minimizing cross-contamination of samples.

Contamination of water samples by the pump mechanism and atmosphere was minimized by the use of a peristaltic pump. The pump was connected to piezometer tops through silicone tubing and polyethylene connectors. In most cases, an air-tight seal was obtained at the piezometer top and the groundwater thus remained isolated from the atmosphere as it passed through the piezometer screen, tubing, and pump. In a minor number of cases, an air-tight seal could not be made because of embrittlement and cracking of the polyethylene tubing. As a result, either air bubbles were drawn into the tubing during pumping or sufficient vacuum could not be created to obtain water at all (see Chapter 3).

Duration of pumping from any one piezometer in a bundle must be minimized otherwise water may eventually be drawn from a higher or lower level in the aquifer and consequently the sample would not be representative of conditions at the pumped piezometer. In past years, this effect was noted during pH measurements after 10 to 15 minutes at a pumping rate of about 0.5 L/min. The lowering of the water table around a bundle has also been noted when shallow piezometers are pumped (Dave and Lim, personal communication). As a general rule, no piezometer in Area A should be pumped for more than 10 minutes at 0.5 L/min; this results in the removal of 5 to 40 piezometer volumes, depending on the depth of the screen. Because pH values occasionally require more than 5 minutes to stabilize during pumping, the field study was broken into two independent tasks: collection of pH and other data, and collection of water samples.

Field pH was measured by continuously directing pumped water into a covered 150 mL container ("flow cell") containing a combination pH electrode which was inserted through a hole in the cover. Water passed from the flow cell by flowing through an opening in the cover. In this way, water in the flow cell was constantly being replaced and refreshed, and atmospheric disturbance of pH measurements was minimized. The flow cell was kept in a water bath to minimize effects of temperature fluctuation on pH measurement. The water bath consisted of the water that continuously flowed from the cell. Because atmospheric temperatures during sampling in November, 1984, were at or near 0^0C, the water bath was at a temperature of up to 5^0C below in-situ groundwater temperature. This maximum fluctuation of 5^0C is considered to have little effect on pH measurements.

The pH probe and meter were calibrated in nominal pH 7 and pH 4 buffers, which were replaced at least once every 24 hours and were kept in the water bath. Thus the actual value of the pH 7 buffer was about 7.06 and that of the pH 4 buffer about 4.00. For the first day-and-a-half of measurements, the pH meter was calibrated with buffers about once an hour. After the stability of the equipment was established, calibration checks were made about once every two to three hours. Except in one case, calibration checks did not deviate by more than 0.04 pH units from the buffer value. The one exception occurred after pH measurements were made on M13-1 to M13-4 (Appendix A, Table A.3). The pH 7.06 buffer read 7.18; the meter was re-adjusted to 7.06 and the pH 4.00 buffer then read 4.00. This indicates the groundwater pH values of the M13 piezometers can be adjusted by a constant value (-0.12 pH units in this case) rather than a pH-dependent value (see Linnet, 1970, for further discussion of pH meter behavior). For all pH measurements, water was pumped at a rate of about 0.5 L/min through the flow cell until a drift of less than 0.02 pH units/min was noted and the value was then recorded as field pH (Appendix A, Tables A.1 and A.3). Approximately five minutes of pumping was often required before the pH stabilized. The pH probe and cell were rinsed with distilled water between each measurement.

Electrical conductivity of the water was measured by taking a sample of about 100 mL in a small container after pH had been recorded. Because the cell constant of the conductivity cell increased sharply then decreased through the field study, the cell constant was measured at each bundle with KCl standards. Conductivity was later corrected to 25^0C and recorded as uSiemens/cm in Appendix A, Tables A.1 and A.3. However, because conductivity measurements are insensitive to neutral-charge aqueous complexes and because up to half of the aqueous ions in the plume water exist as neutral complexes, electrical conductivity is not considered a reliable quantitative parameter in this study.

The second phase of the field study, which began after all pH measurements had been taken, involved water sampling and field alkalinity titrations. Based on the sampling program of previous years and the pH and conductivities of the 1984 survey, fifty piezometers were selected for water sampling and subsequent laboratory analysis. Water was pumped via a peristaltic pump through a 142 mm disk filter assembly containing 0.45 um nitrocellulosic filter paper. New filter paper was used for each sample. After pumping the piezometer for a few minutes and after flushing the system with about 1 liter of groundwater to wet and stabilize the filter and to rinse the sample container, the filtered water was directed into a 4 L polyethylene, collapsible container. After collection the sample was acidified with 30 mL concentrated HCl/L of sample, lowering the pH of the sample to about 1.5. (Analytical results in Appendix A, Table A.3, were adjusted by 3% because of the HCl dilution.) A separate, unacidified 100 mL sample was collected for chloride analysis only. The filter assembly was rinsed with distilled water and a new filter was installed before the next sample was taken.

While the water was filling a sample container, a smaller container was rinsed with distilled water, rinsed with filtered groundwater, and then filled with about 50 mL of groundwater. This water was titrated for alkalinity using standardized HCl. Although alkalinity may not be wholly attributed to HCO_3, Morin (1983) found that, in plume waters, measured Dissolved Inorganic Carbon (DIC) compared well with calculated DIC by assuming the concentration of HCO_3 was equal to alkalinity. This assumption is also considered valid for this 1984 study.

Five of the fifty piezometers were selected for duplicate sampling: M1-7, M2-2, M14-2, M24-5, M25-7. Because over 10 L of groundwater had to be pumped from each of these five piezometers, water quality was expected to change during sampling as water moved from a higher or lower elevation in the aquifer into the screen. This problem had two major implications. First, because representative water may not be obtained, only non-strategic piezometers were chosen. Second, because water quality could change during pumping, one large sample had to be taken and homogenized before splitting into replicates, otherwise comparison of "replicate" analyses could be invalid. Therefore, the following technique was used for each of the five piezometers. A 15 L plastic bucket was rinsed with distilled water, rinsed with diluted HCl (pH 1), rinsed with distilled water, shaken dry, and covered with a sheet of thick styrofoam. Tygon tubing carried water from the filter assembly into the bucket through a hole in the styrofoam. As the water was filling the bucket, the bucket was occasionally agitated to assist in mixing of water and concentrated HCl was added (30 mL HCl/1 L water). When the bucket was filled, it was gently agitated then the water was poured into seven, 4 L polyethylene collapsible containers. The containers were marked with various piezometer numbers so that all appeared as an integral part of the sampling program from different locations. Sample distribution for the seven containers was: three to the Process and Development Laboratory of Rio Algom Limited (PDL), two to the Elliot Lake Laboratory of CANMET (CAN), and two to Guelph Chemical Laboratories Limited (GCL) (Table 1). Table 2 contains the letter requesting analysis issued by Morwijk Enterprises to each of the laboratories.

As a general indicator of variation in water quality during pumping of the large 15 L sample, two alkalinity titrations were made during pumping - at the beginning and the end. For the three samples with pH > 5 (alkalinity > 30 ppm HCO_3), variation in alkalinity was less than 10 percent or within analytical accuracy; for the two samples with pH < 5 (alkalinity < 30 ppm HCO_3), variation was between 20 and 25 percent. This indicates that there was no major variation in water quality during pumping. The two alkalinities for each sample are recorded in Appendix A, Table A.3.

Samples for PDL were delivered within 48 hours of sampling and were stored at ambient temperature in the laboratory. Samples for CAN were delivered within 8 hours and stored at ambient temperature. Samples for GCL were delivered within 10 days and stored at ambient temperature.

2.2. Laboratory Methods

The laboratories involved with this study are: Process and Development Laboratory of Rio Algom Limited (PDL), Elliot Lake Laboratory of CANMET (CAN), and Guelph Chemical Laboratories (GCL) (Table 1). Water samples, including duplicates, were submitted to these laboratories with the letter reproduced in Table 2. The letter follows the recommendations of Keith et al. (1983). Choice of the analytical techniques was left to the individual laboratory (Table 3).

Because PDL analyzed these waters for most of the previous years, it again received the bulk of the samples in order to maintain consistency: one sample from each of the fifty selected piezometers as well as two additional replicates each from five of the fifty piezometers for a total of sixty samples (see previous section). In other words, PDL performed triplicate analysis on five of the fifty piezometers. Most of this report is based on the analytical results from PDL and the replicates serve as an independent check on the reported precision of analysis (Tables 3 to 6).

The two other laboratories received ten samples each: two replicates each from the same five piezometers sampled in triplicate for PDL. The duplicates submitted to each laboratory provide an independent check on the reported precision.

Interlaboratory comparison of mean values (or variances) allow an evaluation of analytical accuracy and reliability of the techniques. The statistical treatment of precision and accuracy can be found in Section 4.3.

3. PRESENT CONDITION OF THE PIEZOMETER NETWORK

The Nordic site can be thought of as a field geochemistry laboratory. The piezometers are the instruments through which geochemical data are gathered. Siting, construction, and installation of these piezometers cost more than one hundred thousand dollars and several thousand person-hours. And like any scientific instrument, the piezometers deteriorate with time and require remedial action. Piezometers at the Nordic site have been in the ground for up to five years and it is estimated that these piezometers will remain useable for a maximum of another two years unless remedial action is initiated.

The piezometers in the plume area (Area A), which are primarily made of polyethylene, extend at least 15 cm above ground surface. Exposure to sunlight and weather extremes has caused embrittlement of the exposed polyethylene and, as a result, several piezometers are cracked and chipped and some piezometer tubes have split down to ground surface. This prevents the tight seal required during pumping to prevent mixing of air with groundwater and, in some cases, sufficient vacuum could not be created to draw water (Section 2.1). Several bundles along the "centerplane" of the plume are covered with large cylindrical iron caps; this has slowed but not stopped the embrittlement process. Also, some bundles have been vandalized: piezometer tubing and identification tags have been removed from a few bundles. Bundle M9 is missing several of its piezometers, which have apparently been broken off 10 to 20 cm below ground surface.

Below ground surface, the piezometers have long been in contact with high-iron, high-sulfate groundwater. There is some evidence that PVC and PVC glue deteriorate in such high TDS waters and, thus, the integrity of the PVC center pipe in each bundle is unknown. Pumping of the center pipe may cause groundwater from several levels in the aquifer to enter the pipe around and through connectors and joints. Integrity of the polyethylene piezometers is also unknown. However, the inertness of the polyethylene, the thickness of the polyethylene, and the one-piece construction of each piezometer suggests there are currently no problems beneath ground surface.

Remedial action of the piezometer network should consist of two phases. First, the total depths of all piezometers should be re-measured in order to re-identify each piezometer in every bundle. Secure, weatherproof markers, bearing both the bundle number and the individual piezometer number, should then be attached to the piezometers. The second phase of remedial action involves piezometer integrity. There are three viable alternatives for correcting the problems. First, exposed lengths of piezometers could be removed and new lengths of inert tubing attached. Second, smaller diameter tubing (much less than 0.9 cm) could be installed within each piezometer. Third, smaller diameter tubing with a permanent packer near the base could be installed within each piezometer. The third alternative would eliminate problems caused by polyethylene rupture anywhere above the packer. All alternatives would continue the desirable dedicated sampler scheme. All alternatives include other advantages and disadvantages.

4. RESULTS AND DISCUSSION

4.1. Review of Terminology

Morin (1983) examined geochemical trends in Seepage Area A along four cross-sections: A-A', B-B', C-C', and C-C" (Figure 3). Cross-sections A-A' and B-B' are essentially perpendicular to groundwater flow; B-B' is relatively unimportant and is not examined in this report. Cross-sections C-C' and C-C" are essentially parallel to groundwater flow, through the center of the contaminant plume. Therefore, any trends in aqueous constituents along these two cross-sections represent the operation of geochemical reactions as the groundwater flows, rather than two or more bodies of groundwater obliquely crossing C-C". The two-dimensional vertical plane along C-C' (from bundle M1 to M10, Figures 3 and 4) is called the centerplane of the plume; from M10 to M14 is the far centerplane. The one piezometer in each bundle that lies directly in the center of the plume forms the one-dimensional centerline.

4.2. Physical Hydrogeology

The stratigraphy in Seepage Area A is relatively simple (Figure 4). The sand aquifer consists of a medium-grained upper sand and a very-fine-grained lower sand. The acidic plume lies in the upper sand near the water table. Average linear groundwater velocities in the upper sand are: approximately 440 m/yr in the vicinity of M1, about 180 m/yr near M9, and about 40 m/yr past M10. Further background details on the historical geology, stratigraphy, and physical hydrogeology of the Nordic site are given in Chapter 4 of Morin (1983).

In years previous to 1984, this field study was carried out during summer months. During these months, there is little infiltration through the unsaturated zone to the water table in Seepage Area A, the dam, and the tailings, because of relatively high rates of evapotranspiration. Also, because the study was conducted each summer, only average yearly behavior was examined, and seasonal variations were eliminated. In 1984, the field study was conducted in mid-November. Ground surface was noticeably moist and rates of evapotranspiration were no doubt low. As a result, the water table in Area A was approximately 1/2 to 2 meters higher than all previous elevations and noticeable distortion of the plume occurred (discussed in following sections of Chapter 4). Shallow piezometers that were consistently dry in past years contained water. The required identification of probable seasonal effects and the required separation of seasonal effects from yearly effects for yearly comparisons complicated the 1984 study.

In addition to unusual conditions in Area A noted in November, there were apparently unusual effects on the Nordic Main tailings. The "seepage collection ditch" that flows off the tailings and around the perimeter of the tailings (Figure 1) often has a pH of about 5 and a conductivity of several thousand uS/cm in the vicinity of Area A. In November of 1984, pH was 3.43 and conductivity was 1890 uS/cm.

4.3. Quality of Geochemical Data

The quality of 1984 field data and the field methods used to ensure reliable measurements are given in Section 2.1. Measurements of pH in 1984 are accurate to within 0.04 pH units. Although calibrated against KCl standards, accuracy of electrical conductivity measurements is taken to be 20%. Accuracy of field titrations of alkalinity is often reported as 10%.

In past years, the quality of laboratory data on Seepage Area A water was evaluated through a few duplicates and cation-anion balances. The few duplicates indicate precision is about 5% to 10%.

As a check on accuracy, errors in cation-anion balances, defined here as:

$$\text{ERROR} = [(\text{CAT}-\text{AN})/0.5(\text{CAT}+\text{AN})] \times 100\%$$

where CAT = sum of cations in epm

AN = sum of anions in epm

are only sensitive to major-ion analysis and, in Area A, often sensitive to only Fe and SO_4

analyses. Cation-anion balances along the centerplane from M1 to M27 inclusive are:

	Mean(%)	Standard Deviation(%)	
1980	+7.98	7.42	(from Morin, 1983)
1982	+1.10	1.11	(from Morin, 1983)
1984	+6.18	6.29	

Balances errors in the far centerplane (from M10 to M14 inclusive) are "up to many tens-of-percent" in 1980 and 1982 (Morin, 1983), and in 1984 have a mean of +13.63% with a standard deviation of 32.23%. Figure 5 displays the errors as a function of conductivity (the far centerplane has the lowest conductivities). The open circles represent re-analysis of SO_4 for five samples, resulting in lower errors. Thus, the cause of the highest balance errors is seen to be lower reliability of SO_4 analyses at low conductivity.

Cation-anion balance is only an approximate test of accuracy and is not indicative of trace-ion accuracy. As a result, a major objective of this study was the detailed evaluation of precision and accuracy for all relevant aqueous constituents. In order to accomplish this objective, water samples were distributed to three laboratories: Process and Development Laboratory of Rio Algom Limited (PDL), Guelph Chemical Laboratories (GCL), and the Elliot Lake Laboratory of CANMET (CAN) (Table 1).

From the fifty piezometers selected for sampling, five were selected for collection of replicate samples. Special care and methodology were used to ensure replicates were identical (Section 2.1). Seven replicates were collected from each of the five piezometers. Three of the seven replicates were delivered to PDL, two to CAN, and two to GCL; each set was marked as unrelated samples. Along with replicates, the letter reproduced in Table 2, which follows the suggestions of Keith et al. (1983), was also submitted. Analytical techniques were not specified by Morwijk Enterprises, but were left to the discretion of each laboratory (Table 3).

In order to maximize the evaluation of replicate analyses for precision and accuracy, several tests were used: visual comparison of means and standard deviations (Table 4), coefficient of variation or CV for each piezometer (Table 5) and for each laboratory (Table 6), and an ANOVA test (Tables 7 and 8). CV is defined as:

CV = (std dev/mean) x 100%

where the standard deviation and mean for each laboratory's analysis are calculated from results of the replicate analyses. ANOVA (Analysis of Variance) is explained in standard statistics textbooks. A weakness in the following data quality evaluation is the assumption of normal distribution, which cannot be tested by the two or three replicates submitted to each laboratory.

Total precision for each laboratory will be examined first, employing CV values (Tables 5 and 6). For most major cations and metals, except Fe, PDL reports a precision of 5% above 0.2 ppm and of 10% to 20% below 0.2 ppm (Table 3). In agreement with reported precision, CV values calculated from PDL replicates are < 5% for major cations and around 20% for most heavy metals, which are at concentrations of less than 3 ppm. However Cu has an overall precision of 68%. In dilute waters (concentration < 0.2 ppm), the precision for trace metals is generally greater than 60%.

CV values for most major ions and metals calculated from CAN replicates are in general agreement with those of PDL. However, CV values from GCL replicates are noticeably higher than those of PDL. The reasons for these higher GCL values are believed to be differences in methods and the relative inexperience of GCL and the experience of PDL and CAN in analyzing uranium-tailings derived water with a complex aqueous matrix. In summary, the total precision for major cations and metals (except Fe) are generally good to fair and are generally in the range reported by PDL. CV values of other laboratories suggest the importance of experience in analyzing this type of water.

For Fe, PDL reports a precision of 5% while replicate-based precision was found to be 0.8% for high Fe concentrations and 6.3% for low Fe concentrations (< 100 ppm). CAN values for Fe are similar while those of GCL are noticeably higher. Analytical methods may not account for the higher GCL values (PDL used wet-chemical titration, CAN used direct current plasma, GCL used atomic absorption from Table 3) and, thus, experience may again play a role in precision.

Among all three laboratories, total precision of SO_4 analyses from CV values is 1% to 7% for concentrated waters and 29% to 78% for dilute waters ($SO_4 < 1000$ ppm). The lack of reliable SO_4 analysis at relatively low concentrations is a common problem in past studies (Morin, 1983) and is discussed above under error in cation-anion balance. SO_4 reliability can be greatly improved when erroneous SO_4 values are identified through error in balance and are re-checked: in the 1984 study, an SO_4 re-check was requested of PDL on an M14-2 replicate and, as a result, the CV value for M14-2 dropped from 77.81% to 18.40%. The effect of SO_4 re-analysis can also be seen as open circles in Figure 5. It is not clear whether the method chosen for SO_4 analysis has an effect on precision. On the other hand, SiO_2 precision is apparently related to analytical methods. PDL uses a gravimetric method with a reported precision of 10% to 20% (Table 3); however, CV values are about 60% for PDL SiO_2 analyses. GCL and CAN use a spectrophotometer and a direct current plasma instrument, respectively, and overall CV values are 10.17% and 2.55%, respectively. Based on these findings, the gravimetric method used by PDL should not be used for these waters.

Total Cl precision is complicated by the fact that it is measured in unacidified water (Section 2.1). Thus, Cl is measured in a sample that has undergone Fe oxidation and precipitation, and subsequent pH depression. The effects of Fe precipitation and pH decrease on aqueous Cl are not known, but anion adsorption may have occurred. Also, storage time of the unacidified sample (Section 2.1) may have an effect on Cl concentrations. These problems may account for the relatively high CV values for Cl, although PDL values of 2.48% for dilute waters and 15.70% for concentrated waters are in the acceptable range. The better CV values for PDL over the other laboratories may be related to analytical method (Table 3).

CAN did not analyze for NH_3 in 1984. GCL total precision is about 12%, close to the reported precision of 13% for its spectrophotometer-based method. PDL total precision is about 4%, close to the reported precision of 5% for the specific-ion electrode method.

PDL and CAN did not analyze for NO_3 in 1984. PDL declined to measure NO_3 because of the anticipated poor results at concentrations around 2 ppm in Area A waters. GCL performed NO_3 analyses and an overall CV value of 22.44% is calculated from replicate results.

CV values for Ra-226 precision are generally around 10% for relatively high levels and about 30% for low levels (around 3 pCi/IL). However, CAN analyses show a CV value of about 40% for relatively high levels.

CV values are not available for Th for two reasons. First, all Th values in Area A are less than the reported detection limit of about 1 ppm (except in 1983). Second, there was insufficient quantity of water for several replicates. PDL is interested in developing a better method for Th analysis similar to the extraction method for U (below), although detection limit would probably decrease to only 0.3 ppm.

There are few CV values for U because many analyses were below detection limit (about 1 ppm) and because there was insufficient water for several replicates. CAN found concentrations in M1-7 replicates above 1 ppm and a CV value of 4.93% is calculated. PDL found a few replicates and non-replicate samples with concentrations above 1 ppm and found good agreement with x-ray and fluorimetric methods. However, in order to obtain a lower detection limit of 3 ppb, PDL used an extraction-fluorimetric method (Table 3) with a reported precision of 5% to 20% depending on concentration. Unfortunately, the overall CV value for this method is 70.66%, indicating poor precision. Therefore, there are no precise measurements of U at concentrations less than about 0.1 ppm in Area A waters.

In summary of precision, total precision of most major-cation and minor-cation analyses based replicate analyses is very good for laboratories experienced in analyzing such waters. Precision of heavy metals (< 3 ppm concentration) is good to acceptable, but unacceptable at concentrations below 0.3 ppm. SO_4 precision is good at high concentrations, but is poor at low concentrations. Careful re-analysis of low-SO_4 samples yields better precision. SiO_2 precision is good, except for samples analyzed by the gravimetric method. Cl precision is acceptable to poor; the poor precision may be related to the unpreserved state of the sample for Cl analysis. NH_3 precision is good to acceptable. NO_3 precision is poor. Ra-226 precision is usually good at high levels and poor at low levels. U precision is poor below about 0.1 ppm. Because PDL performed sample analysis for all study years except 1983 and because only 1984 PDL values are compared to past years, it is important to note that PDL analyses are among the most precise except for SiO_2.

Accuracy of analyses will now be examined. This examination is based on the hypotheses that, for each particular ion, the concentrations in all seven replicates are identical and, thus, the mean concentrations for all laboratories are identical. Visual inspection of means for concentrated waters (e.g. M1-7 in Table 4) indicates that means vary 1) up to about a factor of 2 for major ions, 2) up to a factor of 7 for minor ions, and 3) up to an order of magnitude for trace metals and radionuclides. These variations are somewhat greater in more dilute water (M14-2 in Table 4).

There are several important points related to the above variations. First, in this 1984 study, only PDL results are compared to past years, because PDL has performed Area A analyses since 1979 except in 1983. Because of good continuity in personnel and techniques since 1979 and because of experience with uranium-tailings-derived water, PDL analyses are taken to be accurate. Second, the aforementioned variation in means is believed to be partly the result of not using analytical standards with an aqueous matrix similar to that of the sample, i.e. a high-iron and high-sulfate matrix. Third, although a large variation in means is noted, the standard deviations are also important. If standard deviations are large, then large variations in means has little significance. This relationship can be examined by Analysis of Variance (ANOVA), which tests whether means from the three laboratories in this study are identical (accurate) by testing the ratio of (variance between laboratories / variance within laboratories). The limitation of this test should be understood: if there is a large variance between laboratories, such as for Cu, and there is a large variance within each laboratory's replicate analyses, then the ion will pass the ANOVA test. In other words, the means will be accepted as identical or accurate. A further limitation of this test as applied to this study is the small number of replicates (2 or 3) submitted to each laboratory from which means, standard deviations, and other test parameters are calculated.

Table 7 contains the results of the ANOVA tests (or student t-tests when only two laboratories are involved) for each ion from each piezometer, indicating the acceptance or rejection of identical means on the 95% and 99% confidence levels. Table 8 summarizes Table 7 as the percentage of tests for each ion showing acceptance. Results in Table 8 are artifically high or low for dilute water because only M14-2 is involved and, as a result, only 0 and 100 can appear. Because of this, dilute water is not examined independently of concentrated water. Based on Table 8, Fe and Cu accuracies are excellent; Cu accuracy is high because of the limitation mentioned in the previous paragraph. Na, Zn, Ni, and Cl accuracies are fair to good. Ca, Mg, K, Co, and SO_4 accuracies are weak to fair. Mn, Al, Pb, SiO_2 NH_3, and U accuracies are poor.

Another portion of this data quality study was the submission of two Ra-226 standards prepared by the Department of Chemistry at the University of Waterloo (UW) (Table 1). The standards nominally contained 105 pCi/L and 10.5 pCi/L, respectively, in an aqueous matrix of 0.1 molal Fe and SO_4, acidified to a pH of about 1 with HCL. With this matrix, the Ra standards simulated Area A groundwater. Results of Ra-226 analyses were:

UW	PDL	PDL(repeat)	CAN
105	1609	1399	1574
10.5	513	461	548

The Department of Chemistry (UW) subsequently found that a technician made an error during standards preparation. The nominal 105 pCi/L standard actually contained about 1525 pCi/L; notes on the nominal 10.5 pCi/L standard could not be evaluated. Therefore, Ra-226 results are:

UW	PDL (mean)	CAN
1525	1504	1574
?	487	548

Teeating the UW value of 1525 pCi/L as the true value, the relative error for PDL and CAN results are -1.38% and +3.21%, respectively. This accuracy is very good and and generally does not agree with accuracy based on the ANOVA test, possibly because the Ra-226 level in the standard is more than an order of magnitude greater than found in Area A waters. Because PDL analyzed the standards twice, precision can be determined. The CV values for the higher and lower standsrds are 9.87% and 7.55%, respectively, which agree well with the average CV of 10.77% for concentrated waters in Area A (Table 6).

In summary, precision and accuracy were found to be variable. Precision using CV values shows a general relationship with concentration, while accuracy based on ANOVA or student t-tests shows little to no relationship to concentration.

PDL analyses are among the most precise in this study, except for SiO_2. Accuracy of PDL analyses cannot be determined independently of the other two laboratories by the ANOVA test. However, based on other geochemical parameters (Morin, 1983), PDL analyses appear to be generally accurate. Also, because the remainder of this report deals with geochemical trends and contaminant fronts measured by PDL in past years, the use of PDL results in 1984 is justified by the good continuity of personnel and techniques since 1979.

4.4. Review of the Conceptual Model of Contaminant Behavior

As explained in Chapter 1, a large amount of research has been carried out on Seepage Area A. One part of this research was the formation of a conceptual model of contaminant behavior. This model is reviewed here because the remainder of the report draws heavily on it. Little evidence is presented here for the operation of the model in Area A; detailed evidence can be found in Morin (1983) and Morin and Cherry (in review).

The plume in Area A can be divided into three regions based on the centerplane profiles of the aqueous concentrations for pH, iron, which is the major cation, and sulfate, which is the major anion (examined in detail in Section 4.7). Following the terminology of Morin et al.(1982), the inner core has a pH < 4.8, iron > 5000 ppm, and sulfate > 11000 ppm. The inner core lies near the water table and extends laterally to about 10 m from the base of the dam. The outer zone has a pH > 5.5, iron < 2500 ppm, and sulfate < 7000 ppm. The outer zone lies under the inner core near the dam and it extends southward beyond the inner core, where it occupies the full saturated thickness of the aquifer from about M9 outwards. The outer zone is composed of both pH-neutral process water at depth and altered ex-inner-core water near the water table. The transition region between these two zones is the neutralization zone in which pH increases and concentrations of iron, sulfate, aluminum, nickel, radium-226 and many other species decrease as water flows through this zone.

Because no major chemical reactions occur in the inner core, it can be considered a passive feature; the outer zone is also passive, except for minor carbonate reactions. Thus the neutralization zone is the active zone in which aqueous species are removed from solution, i.e. are retarded by liquid-solid interactions, especially precipitation-dissolution of minerals.

Yearly profiles of pH and iron along the centerline demonstrate that the rate of movement of the neutralization zone is dependent on the value of pH or concentration of iron chosen for comparison; the higher pH values (or lower iron concentrations) on the downgradient side of the neutralization zone show a higher rate of movement than the upgradient side. The reason for this difference in rates is that distinct sub-regions comprise the neutralization zone and each sub-region has a unique migration rate (Figure

6). Nevertheless, an average rate of movement is about 1 m/yr. Because the groundwater velocity is approximately 400 m/yr, the retardation factor for the neutralization zone is 1/400 or 0.2% of groundwater velocity. The precipitation-dissolution reactions that cause this significant retardation of tailings-derived constituents will now be examined.

In Seepage Area A, iron minerals, aluminum minerals and a few other compounds are important as controls of aqueous concentrations of iron, aluminum, and sulfate. When these minerals precipitate upon pH neutralization, the co-precipitation and adsorption of heavy metals and radionuclides also occurs. Thus precipitation directly or indirectly accounts for the decreasing concentrations of most ions through the neutralization zone. Direct identification of these minerals on the sand matrix has not been accomplished because they usually comprise less than 1 weight-percent of the sand, and thus are below the mineralogical detection limit of standard methods. The exception is calcite, which has been detected in thin-section analysis. The presence of carbonate mineral content at an average level of 0.85 wt% in the sand has also been detected by the method of Barker and Chatten (1982).

As the acidic, high-iron seepage from the tailings, which forms the inner core, advances southward in the aquifer, it comes into contact with calcite. Calcite dissolution then neutralizes pH while increasing Ca and dissolved inorganic carbon (DIC) concentrations, as indicated by Equation 1.

$$H^{+} + CaCO_3 \;<\!-\!-\!>\; Ca^{2+} + H_2CO_3{}^{0} \qquad (1)$$

Because inner-core water contains high concentrations of SO_4 and is at saturation with respect to gypsum, the release of Ca into solution causes the precipitation of gypsum:

$$Ca^{2+} + SO_4{}^{2-} + 2H_2O \;<\!-\!-\!>\; CaSO_4 \blacksquare 2H_2O \qquad (2)$$

This accounts for the observed decrease in SO_4 and only minor changes in observed aqueous Ca through the neutralization zone.

For Fe, most of which is Fe^{2+} in Area A, the increase in DIC by Equation 1 can cause the precipitation of siderite:

$$Fe^{2+} + H_2CO_3^0 <--> FeCO_{3(s)} + 2H^+ \qquad (3)$$

If oxidation could occur the increase in pH would cause precipitation of $Fe(OH)_3$:

$$Fe^{2+} + 3H_2O + X <--> Fe(OH)_3 + 3H^+ + Y \qquad (4)$$

where X and Y are a redox couple that allow the change in valence of iron from 2+ to 3+. The contribution of these two mineral-precipitation reactions to Fe removal in the plume has been evaluated through many methods (Morin, 1983; Morin and Cherry, in review). For example, the grouping of data points along the upper boundary of the stability field for $Fe(CO)_3$ in Figure 7 suggests that precipitation of siderite controls the concentration of Fe^{2+} at neutral pH values. This fact, along with other lines of evidence, indicates that nearly all Fe precipitates as siderite.

An additional complexity is that siderite often does not precipitate directly when calcite is present, but instead replaces calcite:

$$Fe^{2+} + CaCO_3 <--> Ca^{2+} + FeCO_3 \qquad (5)$$

Relative to Equations 1 and 3, this reaction does not significantly affect acidity or DIC levels, but contributes to the concentration of Ca, thereby causing gypsum precipitation.

Most of the aqueous aluminum is probably removed from solution upon pH neutralization by the precipitation of gibbsite:

$$Al^{3+} + 3H_2O <--> Al(OH)_3 + 3H^+ \qquad (6)$$

Saturation-index calculations indicate that a dehydrated form of gibbsite (e.g. boehmite) and allophane (amorphous alumino-silicate) probably precipitate in certain areas in place of $Al(OH)_3$. The aluminum mineral and its representative solubility are different for each sub-region of the neutralization zone, and aluminum solubility, expressed as the ion activity product $[Al^{3+}][OH^-]^3$, varies over 2 orders of magnitude through the neutralization zone.

When all of the above precipitation-dissolution reactions are considered, the following conceptual model for solute behavior and migration is formed. When inner-core water first moves into a portion of the aquifer containing calcite, calcite dissolves to neutralize pH, siderite replaces calcite, and gypsum and aluminum minerals precipitate. When calcite is depleted, siderite and then aluminum minerals dissolve in sequence (reverse of Equations 3 and 6), neutralizing pH, but to a lesser extent than calcite. As a result, a theoretical step function for pH and other ions forms along the centerline, with plateaus representing the aforementioned sub-regions of the neutralization zone (Figure 6). The length of each sub-region increases with time and each sub-region migrates faster than the adjacent upgradient sub-region (Morin, 1983).

In order to predict the equilibrium chemistry in each sub-region and to simulate the migration of these zones, a family of one-dimensional cell computer programs named ADNEUT (Acid-Drainage NEUTralization) was created (Morin,1983; Cherry et al.,1984). These models have assisted in clarifying the details of acidic contaminant behavior and of migration in subsurface flow systems through sensitivity studies, simulation of observed data, simulation of plume development in Area A, and simulation of possible future migration in Area A.

An evaluation of the effects of sorption and co-precipitation on the heavy metals and radionuclides indicate that co-precipitation with major minerals is probably more important than adsorption (Morin, 1983). Results from a radionuclide speciation-saturation index model (Morin 1983), indicate direct precipitation of radionuclide compounds such as $Th(SO_4)_2$ and $USiO_4$ may also be occurring in the neutralization zone. Because of the operation of this mixture of processes, the migration of heavy metals and radionuclides in the aquifer is more difficult to simulate than major ions.

The above conceptual model and ADNEUT have also been successfully applied to several uranium-tailings seepage sites in Wyoming (USA) and Bancroft, Ontario (Morin, 1983). Additional details and further applications of the conceptual model can be found in the publications referenced in this report and papers currently in preparation.

4.5. Plume Cross-section (A-A')

This section deals with geochemical profiles (Figures 8 to 13) along Cross-section A-A' (Figure 3). A-A' is essentially perpendicular to groundwater flow or, in other words, groundwater flow is outwards towards the reader. The following sections of Chapter 4 deal with cross-sections parallel to groundwater flow.

Sodium and chloride are special aqueous constituents of Area A because they are essentially "conservative tracers", that is, ions that are only minimally affected by solid-liquid interactions. As a result, sodium and chloride can be used to define distinct bodies of groundwater with differing water quality in Area A.

Morin (1983) defined two distinct groundwaters flowing through Area A. With Na $<$ 15 ppm and Cl $<$ 20 ppm, the first groundwater is recently infiltrated precipitation that has passed through the tailings and is often acidic. With Na $>$ 30 ppm and Cl $>$ 40 ppm, the second groundwater is pH-neutral "process water" - original slurry water from the 1960's deposition of Nordic tailings which is now draining from the tailings (Dubrovsky, in prep).

Figures 9 and 13 contain Na and Cl profiles for A-A'. These two profiles show that recently infiltrated groundwater is flowing past M25 and M2 near the water table while process water occurs at depth. Near the water table at M1, which is the center of the plume, the groundwater is recently infiltrated precipitation with some apparent mixing of process water based on slightly elevated levels of Na and Cl. This finding is consistent with that of Morin (1983). Although Na and Cl (and pH, Figure 8) indicate that the shallow water at M1 has undergone some mixing, contaminants such as Fe (Figure 8), Al (Figure 10), Co, Zn, Pb (Figure 11), Ni, SO_4 (Figure 12), and Ra-226 (Figure 13) all indicate the center of the plume indeed lies near the water table at M1.

The profiles of all ions closely resemble those of past years, except for the following exceptions. First, the 1984 pH profile (Figure 8) now shows water with pH < 4 near the water table at M2. Because concentrations of contaminants are relatively very low at this location, this is not the beginning of another plume, but probably a seasonal flushing of dilute acidic water during the wet season (Section 4.2). A second exception is that maximum aluminum and radium concentrations are about 1/2 of previous years, suggesting a decreasing source input of these contaminants. Third, Cu shows a peak at M2, but reliability of Cu analyses (Section 4.3) are such that this peak may be erroneous. Fourth, the 1984 SiO_2 profile is quite different from the 1980 profile, but again reliability of analysis is quite low.

The low-pH water (pH < 4) at M2 is at first surprising in light of the conceptual model (Section 4.4). Figure 6 indicates a gradual decrease in pH should be observed at M2 for a few years before an inner-core-type pH appears. This gradual decrease was not obvious. However, the possibility for the occurrence of such a sharp decrease in pH near the dam was recognized by Morin (1983). Based on calcite saturation indices, Morin found that a large region between M25 and M2 was devoid of solid carbonate. The probable cause was a much larger inner-core cross-sectional area in the past which dissolved most or all pH buffering material. Thus the scenario envisioned in the conceptual model cannot occur. The implication is that low-pH water can begin flowing unaffected through a large region between M25 and M2, as is now observed at M2.

4.6. Sodium and Chloride Along the Centerplane (C-C')

This and remaining sections of Chapter 4 evaluate geochemical profiles along the centerplane (C-C') and the far centerplane (C-C"). In this section, only 1984 data are examined because sodium and chloride were not measured in 1983.

Figures 14 and 15 contain the sodium and chloride profiles for both the centerplane and the far centerplane. As explained in Section 4.5, the two distinct bodies of groundwater can be seen: recently infiltrated groundwater, which has passed through the tailings, lies near the water table and process water lies at depth. Close to the dam, recently infiltrated tailings-derived groundwater is synonymous with the inner core of the plume, and the 20 ppm Cl contour marks the approximate base of the contaminant plume. The 10 ppm Na contour marks the approximate base of the peat (Figure 4), which lies in the unsaturated zone during summer months. In the vicinity of M9, the recently infiltrated groundwater nearly disappears based on Na and Cl concentrations. Morin (1983) attributed this "disappearance" to upward vertical dispersion of Na and Cl.

Comparisons of the 1984 Na and Cl profiles with profiles of past years shows that the same contour pattern continues to occur, although 1984 concentrations are about 30% lower in the recently infiltrated water. These lower concentrations are consistent with an increased amount of infiltration during the wet season and the effect of the peat now lying in the saturated zone (Section 4.2); lower concentrations of Cl may also be explained by analytic error (Section 4.3).

There are two problematic bundles, M24 and M20 (Figure 3), which essentially lie on the centerplane. M24 does not show the existence of any recently infiltrated water along its length (Table A.3), perhaps of the wide vertical spacing of piezometer screens or a minor distortion in the flow system. The vertical spacing of screens may allow the plume to pass between two vertically adjacent screens. Because of the ambiguity of results from M24, M24 is not defined as part of the centerplane in 1984, as done in most previous years (Table 9). The second bundle, M20, lies between M1 and M8. In all previous years including 1983, recently infiltrated water (inner-core water) was found near the water table (elevation of about 340 m) at M20. In 1984, only process water was found up to an elevation of 340 m. However, because the water table in November of 1984 was 2 meters higher than in the summers of previous years, the flow system was different and the plume may have passed M20 very close to the higher water table or perhaps between two adjacnt screens as believed for M24. Nevertheless, M20 is not included in the centerplane for 1984 because of this ambiguity. The inclusion of M20 in the centerplane profiles would result in the compression of contour lines near the water table between M1 and M8, as is generally evident on profiles from past years.

Like the centerplane profiles, Na and Cl profiles for the far centerplane (Figures 14.2 and 15.2) show the existence of shallow tailings-derived infiltration water and deeper process water. Also, the infiltration of dilute water to the water table in Area A is apparent at M10. Comparisons with past years indicate lower concentrations in 1984.

4.7. Major Ions and pH

The geochemical trends for pH and major cations and anions, defined as having a concentration greater than 40 ppm in the inner core, are discussed in this section. Because some 1983 data is available for the centerplane and part of the far centerplane, both 1983 and 1984 profiles are presented and discussed. Although the sampling density in 1984 (three piezometers from each bundle on average) was similar to previous years, the 1983 sampling was unique. Complete analyses were not performed on 1983 samples (Appendix A, Table A.2), yet every piezometer in each relevant bundle was sampled. For the parameters analyzed in 1983, this sampling density allows a much better definition of plume thickness and outline.

4.7.1. pH

Figure 16 contains pH profiles for 1979 through 1984 for the centerplane (C-C'); all contour lines were drawn with straight-line interpolation between pH measurements. Unlike other parameters such as Fe, all piezometers in centerplane bundles are sampled for pH, providing a more detailed view of plume variation through the past years. According to the conceptual model and computer simulations, there is no solid-phase control of pH's less than about 5; therefore the pH 4.5 contour line is able to and does display erratic movement. Conversely, pH 5.0, 5.5, 6.0, and 6.5 contours display the yearly migration of acidic water through the aquifer. According to the conceptual model, the pH 6.0 should and does display very rapid movement. The pH 5.5 and 5.0 contour lines display slower movement because they can be taken as representing sub-regions closer to the inner core

(Section 4.4). The average yearly rate of movement of the pH 5.0 line is about 2 m/yr although a smooth yearly progression is not apparent because of piezometer spacing. In the vicinity of M9 and outwards, the yearly movement of the pH 5.0 contour line is predicted to decrease below 1 m/yr.

The 1984 pH diagram shows the effects of a higher water table by the formation of a distinct water mass above the plume. The water with pH < 4.5 at M17 reflects groundwater passing through an acidic portion of the peat (Figure 4); this acidic input is often minor during summer months. The peat-derived water probably has little effect on the plume because its overall chemical composition is similar to plume water.

Figure 17 contains pH profiles for the far centerplane (C-C"). While the 1983 profile shows a decrease in pH from past years, the 1984 profile is more complex. At depth, pH values are greater than 6.5 and infiltration to the water table produces cells of acidic and neutral pH. Further discussion of yearly changes is provided below and in Section 4.11.

4.7.2. Fe

Figure 18 contains Fe centerplane profiles for 1979 through 1984. Straight-line interpolation between point values was used to draw this and following profiles; the 1983 Fe profile, which contains a greater density of measurements shows that interpolation in other years resulted in a consistent shape for the plume. All profiles show a decrease in Fe outwards along the centerplane and centerline. According to the conceptual model, the decrease is primarily the result of siderite replacing calcite (Equation 5). All Fe profiles except 1984 show a movement of Fe contour lines outwards. The 1000 and 2000 ppm contours, representative of the outer zone, move very quickly; this rapid movement is expected (Cherry et al., 1984). The remaining contour lines generally show a relationship of decreasing rate of movement with increasing contour value. This behavior is understandable if each higher contour line is assumed to represent a sub-region closer to the inner core (Section 4.4).

The 1984 Fe profile appears contradictory in that contour lines indicate a retrograde movement towards the dam although the input value (at M1) remains greater than 5000 ppm. The conceptual model of contaminant behavior can account for this problematic trend, and the "problem" of the profile is the result of using the simple (and actually incorrect) approach of examining trends of individual ions. The conceptual model holds that precipitation-dissolution of minerals control most of the contaminant behavior. As a result, trends of many individual ions should not be examined in Area A because mineral solubility is described by the product of activities of at least one cation and one anion (Ion Activity Product). In the case of siderite, solubility is related to the product of $[Fe^{2+}]$ and $[CO_3^{2-}]$.

Using the computer program WATEQ2 (Ball et al., 1979), saturation indices for siderite and other minerals were calculated. The Saturation Index (SI) for a mineral is:

$$SI = \text{ion activity product} / \text{reported solubility} \tag{7}$$

For siderite,

$$SI = [Fe^{2+}]\,[CO_3^{2-}] / K \text{ of siderite} \tag{8}$$

When log SI siderite < 0.0, the water is undersaturated with respect to siderite and siderite is probably not present; when log SI siderite > 0.0, siderite will theoretically precipitate because of supersaturation. Figure 20 contains log SI siderite profiles for 1980, 1982, and 1984; no profile can be made with 1983 data because of the lack of alkalinity data. In all the centerplane profiles, the plume water out to at least M17 is undersaturated with respect to siderite; this water represents the inner core and $Al(OH)_3$ sub-region. The 0.0 log SI contour line marks the approximate upgradient edge of the siderite sub-region; log SI values greater than 0.0 lie in the siderite and calcite (outer zone) sub-regions. Values greater than 0.0 do not represent supersaturation in this case, but are an artifact of carbonate solid-solution behavior (Morin and Cherry, in review).

Taking into account the spacing of piezometers, the slow rate of movement of sub-regions around M9, and the effects of the higher water table in November of 1984, no retrograde movement of the 0.0 log SI siderite contour is apparent from 1980 to 1984. Thus the retrograde movement of Fe contour lines is merely the result of performing the incorrect individual-ion examination. pH does not display retrograde movement because of its unique role in aqueous solutions. These points are discussed further in Section 4.11. Nevertheless, examinations of individual ions is still beneficial to some extent, especially when precipitation-dissolution is not a dominant geochemical control, and will be continued in this report.

Figure 19 contains Fe profiles for the far centerplane. When compared to previous years, the 1983 profile indicates little movement of the 1000 ppm contour (<20 m/yr) and more rapid movement of the 2000 ppm contour (about 60 m/yr). Groundwater velocity through most of the far centerplane is about 40 m/yr and, because Morin (1983) found essentially no retardation of major contaminants, movement of contour lines should also be about 40 m/yr. The disagreement between observed movement in 1983 and expected movement is attributed to minor geochemical reactions occurring in this zone (outer zone) and to the greater density of measurements taken in 1983.

The 1984 Fe profile of the far centerplane shows a movement of about 40 m/yr for all contour lines, in agreement with groundwater velocity. As a result, the water quality in Buckles Creek near M14 can be expected to continuously decrease with time; the degradation can be monitored and evaluated by comparison with the 1982 study of Buckles Creek (Dubrovsky et al., in press). There is no retrograde movement of Fe contours in the far centerplane, as is observed closer to the dam in the neutralization zone, because 1) the far centerplane is part of the outer zone in which precipitation-dissolution of minerals is a minor geochemical process and 2) the far centerplane below a depth of a few meters appears to be less susceptible to transient seasonal fluctuations. The log SI siderite diagram (Figure 21) shows little change from 1982, except dilute, undersaturated water now also occurs at the water table at M12 and M14.

4.7.3. Ca

From this point onwards, profiles prior to 1983 will not be reproduced in this report, but will continue to be verbally examined. Profiles prior to 1983 can be found in Morin (1983).

Calcium plays a unique role in the conceptual model. For each millimole/liter of Fe (about 55 ppm) removed from solution by replacement of calcite with siderite, one millimole/liter of Ca (about 40 ppm) is added to solution. Based on Figure 18, hundreds to thousands of ppm of Ca are apparently added to solution. However, Figure 22 shows that Ca only varies by one to two hundred ppm, except in the peat at M17 in 1984. The reason for the contradiction in Ca concentrations is that all groundwaters in Area A, except at a few locations near the water table, are at saturation with respect to gypsum. Any addition of aqueous calcium is immediately removed by gypsum precipitation (Equation 2) and, thus, calcium remains essentially constant while sulfate decreases sharply (examined below).

Log SI calcite is:

$$\log \text{SI calcite} = \log([Ca^{2+}]\,[CO_3^{\,2-}]/K\ \text{calcite}) \qquad (9)$$

Figure 24.1 contains the log SI calcite profile for the centerplane in 1984, and this profile as well as 1980 and 1982 profiles show the entire centerplane with a log SI < 0.0. This does not indicate that calcite is absent in the aquifer; Morin (1983) shows that calcite is indeed present. Instead, the apparent undersaturation is simply an artifact of the complexity of the calcite-siderite solid solution (Morin and Cherry, in review). Nevertheless, the contour lines can still be used to detect movement. The -2.0 contour, which marks the approximate upgradient edge of the calcite sub-region, shows a movement in excess of 10 m/yr. While a rapid movement is predicted by simulations, a reliable match of simulated and observed rates cannot be obtained because of lack of data on simulating the solubility of the calcite-siderite solid solution (Cherry et al., 1984; Morin and Cherry, in review). With completion of this 1984 study, it may be possible to create an empirical equation to properly simulate calcite-siderite solubility.

Figure 23 contains the Ca profiles for the far centerplane. Both 1983 and 1984 profiles are similar, except the 1983 profile shows the input of dilute water at the water table at M12. Although the Ca profiles display a sharp decrease in Ca concentrations around M13, the log SI calcite diagram (Figure 24.2) does not show a parallel change. As a result, mineral solubility ($[Ca^{2+}]\ [CO_3^{2-}]$ here) is responsible for the Ca decrease: as pH rises above 6.0 and alkalinity increases around M13, the conceptual model dictates that Ca must decrease sharply to maintain calcite equilibrium. However, as will be seen below, many other ions show a sharp decrease around M13 and little movement past M13, indicating the presence of a yet undefined geochemical "trap".

As with the centerplane closer to the dam, all log SI calcite values are less than 0.0, although calcite is no doubt present. Again, the apparent undersaturation is the result of difficulties in representing the solubility of the calcite-siderite solid solution.

4.7.4. Mg

Magnesium is apparently not controlled by precipitation of a magnesium mineral: all magnesium minerals including dolomite are at significant undersaturation in Area A waters according to WATEQ2 (Ball et al., 1979) results. Apparently the only geochemical controls operating on Mg in Area A waters are adsorption and incorporation of Mg into calcite and siderite because $MgCO_3$ is part of the carbonate solid solution. However, the potential for adsorption is minor because sorption sites are swamped by Fe, and Mg shows the least tendency to substitute Fe in siderite (Morin, 1983). Therefore, Mg should behave as a conservative tracer in a major portion of Area A in 1983 and 1984. As anticipated, profiles for Mg (Figure 25) display no significant trend although a decrease in concentration at M1 is apparent.

Profiles for Mg in the far centerplane (Figure 26) show a concentration peak at depth around M11 and M12 and, like Ca, a sharp concentration decrease at the geochemical "trap" around M13. The cause of the concentration peak is not known. The cause of the decrease at M13 is believed to be the incorporation of Mg with Ca into calcite as CO_3^{2-} increases and Ca decreases in solution.

4.7.5. K

No analyses for K were made in 1983. The 1984 profile for the centerplane (Figure 27.1) closely parallels that of 1980, except the concentration at the water table at M17 is about 1/3 that in 1980. Therefore, there has been little change in overall behavior and little movement in K over four years. The decrease in K at the water table upgradient of M17 is attributed to uptake (adsorption) of K by feldspar minerals in the sand. Although adsorption of K is often significant in many groundwater systems, adsorption is not as strong in Area A because sorption sites are probably dominated by Fe and Ca, which occur in greater concentrations.

In the far centerplane (Figure 27.2), most of the profile is similar to that closer to the dam. In the vicinity of M13, concentrations of K decrease sharply, possibly because of the increased availability of sorption sites as Fe, Ca, and Mg decrease sharply.

4.7.6. Al

Aluminum plays a major role in the conceptual model of contaminant behavior: the precipitation-dissolution of Al minerals results in an $Al(OH)_3$ sub-region and affects the behavior of other sub-regions (Cherry et al., 1984). The movement of the $Al(OH)_3$ sub-region and other sub-regions, approximately represented by the movement of Al contour lines (Figure 28), can be defined by yearly comparison. However, the input value of Al, defined by the maximum concentration at M1, has been decreasing through time, which in turn affects the yearly position of contour lines. As a result, several contours of high concentration have disappeared or show retrograde movement from 1980 to 1984. Using the lowest contour values of 20 ppm and 1 ppm, a movement of about 1 m/yr is found; this rate of movement for the $Al(OH)_3$ and siderite sub-regions is also predicted by the conceptual model (Morin, 1983; Cherry et al., 1984).

One mineral apparently precipitating in Area A is amorphous $Al(OH)_3$:

$$Al^{3+} + 3H_2O \;<\!-\!-\!>\; 3H^+ + Al(OH)_3 \qquad (6)$$

with a log SI expressed as:

$$\log SI = \log([Al^{3+}]\,[OH^-]^3/K\,Al(OH)_3) \qquad (10)$$

Solubilities of other aluminum minerals can also be expressed as $[Al^{3+}]\,[OH^-]^3$. Boehmite is one de-hydrated form of $Al(OH)_3$ that apparently forms in Area A. Using Equation 10, when log SI amorphous $Al(OH)_3$ is approximately 0.0, amorphous gibbsite is present; when log SI amorphous $Al(OH)_3$ is about −1.8, boehmite is present (Morin, 1983). Examination of log SI amorphous $Al(OH)_3$ profile (Figure 30) reveals the presence of amorphous $Al(OH)_3$ near the water table at M19. Cherry et al. (1984) indicate that this mineral marks the location of the siderite sub-region based on simulations of the conceptual model; this location is the same as that defined by the 0.0 log SI siderite contour (Section 4.7.2). The zone marked by 0.0 log SI amorphous $Al(OH)_3$ is moving at a rate of about 2 m/yr, which is about a factor of 2 greater than the rate of the Al contour lines, but which is acceptable in light of the piezometer spacing and sampling density.

Downgradient of the siderite sub-region (away from the dam) is the calcite sub-region; according to simulations, it is marked by a log SI amorphous $Al(OH)_3$ value of about −1.5 (Figure 30). Upgradient of the siderite sub-region is the $Al(OH)_3$ sub-region which is theoretically marked by a log SI amorphous $Al(OH)_3$ value of about −0.5. However, the location of the $Al(OH)_3$ sub-region, which is in the vicinity of M16 and M17, is not apparent on Figure 30 probably because of effects of the acidic peat at M17 and the decreasing input of Al. Nevertheless, significant loss of Al from solution does occur around M16 and M17 in both 1983 and 1984 (Figure 28), indicating the approximate location of the $Al(OH)_3$ sub-region. The effect of the peat at M17 on the behavior of the $Al(OH)_3$ sub-region is not known, but can be examined through simulation (Cherry et al., 1984).

Allophane, an amorphous alumino-silicate, is also present based on the log SI allophane profile (Figure 30.2), although there is some question of log SI reliability because of poor reliability of SiO_2 analyses (Section 4.8.2). Nevertheless, the amount of allophane precipitated appears to be minor based on the minor loss of SiO_2 through the centerplane (Morin, 1983, and below). In the outer zone from M27 outwards, allophane may dominate over boehmite in controlling aqueous aluminum concentrations.

In the far centerplane, nearly all concentrations are close to or below detection (0.1 ppm), except in 1983. Because the 1983 data show significant trends, the data are profiled in Figure 29. The reason for the unusual behavior of Al in 1983 is not known. Based on the few available 1984 log SI values for amorphous $Al(OH)_3$ and allophane (not diagrammed), both minerals may take part in controlling Al concentrations in the far centerplane.

4.7.7. SO_4

The dominant geochemical control on SO_4 in Area A is precipitation-dissolution of gypsum. Because Area A waters are at saturation with respect to gypsum (nearly all log SI gypsum values lie in the range −0.20 to +0.20), addition of calcium to solution by calcite replacement (Sections 4.4 and 4.7.3) causes the precipitation of gypsum and accompanying loss of SO_4. As discussed above in Section 4.7.3, hundreds to thousands of ppm of Ca are probably added to solution and, thus, significant amounts of Ca and SO_4 are removed from solution. Also, adjustments in ion pairing and activities as pH and ionic strength change cause some precipitation.

Figure 31 shows the centerplane profiles for SO_4 in hundreds of ppm. The 1983 profile shows a peak at M20, which is not apparent in other years, and most SO_4 is lost between M8 and M9. The 1984 profile displays the commonly observed decrease in SO_4 from M1 to M9, although the profile at the water table from M17 outwards is distorted by the addition of dilute infiltration. It is interesting to note that SO_4 in 1984 decreases significantly in the inner core (M1 to about M8), although no geochemical reactions occur in the inner core according to the conceptual model. This significant decrease does not appear in past years and is not predicted in simulations. The explanation for the decrease in the inner core is not known, but may be related to the unusual conditions encountered in November of 1984.

Profiles of the far centerplane (Figure 32) are similar to the 1980 profile, and all contour lines except 1000 ppm show an average movement of about 30 m/yr, in agreement with the groundwater velocity. The 1000 ppm contour has remained in the vicinity of M13 since 1980, indicating the capability of this yet undefined geochemical "trap".

4.8. Minor Ions

The minor ions examined in this section are Mn, SiO_2, NH_3, and NO_3. Heavy metals and radionuclides are examined in the following sections.

4.8.1. Mn

Because Area A waters are undersaturated with respect to Mn minerals, substitution of Mn in solid-phase carbonate, especially siderite, appears to be the geochemical control on Mn (Morin, 1983). Although there are no strong trends on the 1983 centerplane profile for Mn (Figure 33), the Mn contours show a further downgradient extension near the water table than at depth, possibly accounted for by the lack of carbonate that exists in the inner core and $Al(OH)_3$ sub-region. The input concentration of Mn (at M1) fluctuates yearly by a few tens of ppm and, thus, the definition of geochemical controls and the identification of a migrating front cannot be tested. The input fluctuation is most extreme between 1983 and 1984 (Figure 33). The same variability and problems noted closer to the dam also hold for the far centerplane (Figure 34).

4.8.2. SiO_2

SiO_2 is the first ion examined with a poor precision of analysis by PDL; the overall coefficient of variation (CV) is 64.50% (Table 6). As a result, the 1984 SiO_2 profile (Figure

35.2), as well as 1979–1982 profiles are probably not reliable. The 1983 Si profile (Figure 35.1) is probably more reliable because the overall CV for CAN is 2.55% (Table 6). With the greater density of samples, the 1983 profile also best defines the shape of the SiO_2 plume. The sharp decrease in ppm Si near the water table at M17–M18 is consistent with allophane precipitation (Section 4.7.6) near the contact of the $Al(OH)_3$ and siderite sub-regions. Although good precision allows the definition of the Si plume in 1983, the magnitude and accuracy of Si values are questionable based on ANOVA results on 1984 interlaboratory replicates (Table 8).

For reasons explained in the previous paragraph, only the 1983 Si profile for the far centerplane (Figure 36) is discussed. Whereas Si concentrations are observed to decrease along the centerplane, concentrations in the far centerplane show a generally increasing trend. The reason for the increasing trend and for the concentrations peaks at M12 and M13 is not known, but may be related to the variation of allophane with pH (see Appendix C of Morin, 1983, for more details).

4.8.3. NH_3

Figure 37 contains the centerplane and far centerplane profiles for NH_3 in 1984. NH_3 was not measured in 1983 (nor in 1980 and 1981).

The 1984 profile is similar to the 1982 profile, except 1984 concentrations at depth are somewhat higher. Although NH_3 is often strongly dominated by adsorption, Morin (1983) found that NH_3 behaves like a conservative tracer in Area A, perhaps as the result of sorption sites being dominated by major ions. The 1984 data are consistent with this observation and the data can be used, like Na and Cl, to distinguish the shallow recently infiltrated water from the deeper process water.

Concentrations in the far centerplane are significantly higher in 1984 over 1982. Nevertheless, the sharp decrease around M13 occurs in both years.

4.8.4. NO_3

Because of anticipated poor reliability of NO_3 analysis in Area A waters, PDL declined to analyze for NO_3 in 1984. Based on NO_3 analysis of 1984 replicates by GCL, NO_3 values are rather unreliable, with a CV of 22.44%. The reason for the poor precision is the relatively low concentrations of a few ppm in Area A waters; this same problem plagues heavy metal analyses. Because of the relative unimportance of NO_3 at the site and the poor analytical reliability, NO_3 is examined no further.

4.9 Heavy Metals

The metals examined in this section are Cu, Co, Zn, Pb, and Ni; other metals can be found above. All metals examined here occur at concentrations of a few ppm or less, and this relatively low level produces analytical problems. Total precision calculated from replicates (Tables 5 and 6) nearly always exceeds a CV value of 10%, and CV values greater than 100% are calculated. However, accuracy calculated through ANOVA or student t-tests (Tables 7 and 8) is satisfactory to good, which generally indicates the variance in results from each laboratory is close to the variance between laboratories. In summary, observed trends through the centerplane and far centerplane for Cu, Co, Zn, Pb, and Ni may be questionable.

Saturation indices for heavy-metal minerals are all significantly undersaturated according to WATEQ2 (Ball et al., 1979) calculations. Therefore, despite poor precision, precipitation-dissolution of heavy-metal minerals is not likely occurring in Area A. This leaves co-precipitation and, perhaps, adsorption as dominant controls of heavy metals (Morin, 1983).

4.9.1. Cu

Morin (1983) found that up to several tens-of-percent of dissolved Cu exists as Cu-organic complexes based on WATEQ2 calculations incorporating 1979 DOC measurements. This finding indicates that the geochemical behavior of Cu and, presumably, other trace metals is affected but not seriously altered by organic complexing.

Figure 38 contains the 1984 Cu profile for the centerplane. Cu was not measured in 1983, and Cu is usually below detection limit in the far centerplane. Figure 38 displays the typical profile of decreasing concentration with lateral distance near the water table. This trend, which can be accounted for by adsorption and co-precipitation, is taken to be real although precision of Cu analyses (Tables 5 and 6) is the worst of all heavy metals. The accuracy of Cu analyses based on student t-tests (Tables 7 and 8) is excellent because the variance of each laboratory's analysis is very large.

4.9.2 Co and Zn

The precision of PDL analysis for Co and Zn is very good for concentrated (> 3000 mg/L TDS) water (Tables 5 and 6). As a result, trends on centerplane profiles are probably reliable while trends on far centerplane profiles are questionable.

The Co (Figure 39.1) and Zn (Figure 40.1) centerplane profiles show a concentration decrease along the water table. The decrease between M1 and M8 may be the result of adsorption in the inner core or the result of the unidentified process also causing SO_4 decrease in the inner core (Section 4.7.7). Between M17 and M19, the decrease is probably the result of dilute water from the peat at M17. Decreases beneath the past and water table in past years were attributed to the incorporation of Co and Zn, which form part of the carbonate solid solution, into calcite and siderite.

Comparisons with past profiles indicate that the overall Zn profile has remained essentially static while the overall Co profile shows some movement. The quantitative assessment of Co movement is difficult because the input value at M1 is less in 1984 and the peat at M17 distorts the Co plume.

Trends in the far centerplane for Co (Figure 39.2) and Zn (Figure 40.2) may not be reliable because of analytical problems. Nevertheless, the typical concentration decrease in the vicinity of M13 is displayed.

4.9.3. Pb

Precision of PDL analyses for Pb (Tables 5 and 6) in concentrated waters is rather poor; PDL precision for dilute waters is unknown but is believed to be somewhat poorer based on GCL and CAN results.

Centerplane and far centerplane profiles can be found in Figure 41. The observed Pb trends, although questionable, are apparently a decrease in the neutralization zone and in the vicinity of M13. Again, co-precipitation and adsorption are believed to be the geochemical controls on Pb.

4.9.4. Ni

For analyses by PDL, Ni has the best overall precision of all metals examined in Section 4.9 (Table 6) and accuracy based on an ANOVA test is good (Tables 7 and 8). Therefore, observed trends are considered reliable.

Figure 42 contains the 1984 Ni profiles for the centerplane and far centerplane. The centerplane profile shows a concentration of 1.5 to 2.0 ppm in the inner core, which follows the observed yearly trend of decreasing input concentrations of Ni, decreasing to 0.5 ppm around M27. This trend is distorted by the peat at M17. The decreasing trend is probably the result of co-precipitation in the neutralization zone (Morin, 1983). The far centerplane displays the typically higher concentrations along the water table as well as the sharp concentration decrease around M13.

4.10. Radionuclides

The presence of radionuclides distinguishes seepage from pyritic uranium tailings from seepage from other pyritic tailings. The past studies of radionuclides in Area A have included dissolved U, ^{238}U, ^{235}U, ^{234}U, dissolved Th, ^{232}Th, ^{230}Th, ^{228}Th, ^{227}Th, ^{227}Ac, ^{226}Ra, ^{223}Ra, and ^{210}Pb. The 1983-1984 study only examines dissolved U, dissolved Th, and dissolved ^{226}Ra; ^{226}Ra on a molal basis also represents total dissolved Ra in Area A and, thus, "concentration of radium" and "radioactivity of ^{226}Ra" are considered synonymous in this study.

4.10.1. Ra-226

By creating and applying to Area A a radionuclide speciation program (WATRAD), Morin (1983) found that Ra is apparently not affected by precipitation-dissolution of Ra minerals. Thus adsorption and, more likely, co-precipitation controls Ra concentrations. Co-precipitation of Ra with calcite and gypsum appears very likely (see Appendix D of Morin, 1983, for details).

Figure 43 contains Ra-226 centerplane profiles for 1983 and 1984; values in the far centerplane are often less than 5 pCi/L and are not plotted. The overall precision of Ra analyses by PDL is satisfactory (Table 6) and, thus, trends are considered reliable. The sharpest decrease in concentration occurs at the beginning of the neutralization zone (around M16), although a more gradual decrease is noted in the inner core. Thus, adsorption may operate in the inner core while co-precipitation may dominate in the neutralization zone.

Yearly comparisons of Ra-226 are complicated by yearly changes in input values. The changes are probably the result of both actual changes and changes in laboratories performing the analyses (see means for Ra-226 in Table 4). As a result, migration rates of the Ra-226 plume are difficult to define (see Section 4.11 for more details).

4.10.2. Th

Morin (1983) found that thorium is probably controlled by precipitation of Th minerals such as $Th(SO_4)_2$, although co-precipitation and adsorption cannot be reliably ruled out. The problem with examining Th through dissolved Th, as done here, instead of through the dominant Th isotope (^{232}Th), is the difficulty of analysis. PDL detection limit is reported at about 1 ppm and waters in Area A usually contain less than 1 ppm Th. As a result, PDL tested some 1984 samples and ceased analysis upon finding low levels. PDL mentioned the possibility of developing an extraction method for Th, similar to that for U; however, detection limit would only decrease to about 0.3 ppm. The 1980 analyses of Th, by the University of Waterloo and of unknown reliability, show a maximum of 0.1 ppm; molal concentrations of Th isotopes show general agreement with levels of less than 0.1 ppm.

Figure 44 contains 1983 Th profiles for the centerplane and far centerplane. The 1983 Th analyses were performed by the Elliot Lake Laboratory of CANMET. The inner-core concentration is greater than 1.0 ppm and a typical trend of decreasing concentrations, especially a sharp decrease in the neutralization zone, is apparent. Although reliability and detection limit are unknown, the typical trend suggests the data are realistic. The reason for such high values in 1983 is not known.

4.10.3. U

Morin (1983) found that uranium is possibly controlled by precipitation of U minerals, based on WATRAD results. However, as with Th, co-precipitation and adsorption cannot be reliably ruled out.

The detection limit of U analysis by CAN in 1983 is assumed to be about 0.7 ppm based on reported negative concentrations of up to about -0.7 ppm (Table A.2); accuracy and precision in 1983 are unknown. (The detection limit for CAN analyses in 1984 is 0.8 ppm.) In 1984 PDL tried several methods for U analysis, but unreliable results were obtained below 1 ppm (Section 4.3). Therefore, PDL re-analyzed using an extraction method with a reported detection limit of 3 ppb. Nevertheless, overall precision and accuracy are poor (Tables 5 to 8), although at concentrations above about 0.1 ppm, precise results can be obtained (Table 4, M1-7, U). As a result, 1984 PDL values are only used for defining general trends.

In 1980-1982, maximum concentrations at M1 were about 0.5 ppm (although values differed by up to one order-of-magnitude between laboratories) and concentrations consistently dropped below 100 ppb past M8. Figure 45 shows the same trend in 1983 and

1984; the 1984 profile especially displays the trend noted in 1980-1981. The extreme decrease in U concentrations in Area A also suggests the operation of U precipitation over co-precipitation and adsorption (Morin, 1983).

In the far centerplane in 1983 (Figure 46), there is a concentration peak over 5 ppm U around M11 and M12. This peak is not expected in light of solubility and other geochemical constraints and cannot be explained. Uranium has not been examined in this region in other years, so comparisons with past years cannot be made.

4.11. One-dimensional Centerline Profiles and Yearly Plume Movement

In past studies of Seepage Area A, plume movement was defined through one-dimensional profiles. For reasons discussed below, this approach is no longer considered as reliable as before and, thus, plume movement was examined in previous sections on centerplane diagrams. The $Al(OH)_3$ and siderite sub-regions were found to be moving 1 to 2 m/yr and the calcite sub-region was found to be moving about 10 m/yr, in agreement with past findings.

Centerline (Figures 47 to 51) and far centerline (Figures 52 and 53) profiles are drawn by choosing as representing the center of the plume one piezometer from each bundle on the centerplane (Table 9). The choice of piezometers was often made by choosing the piezometer with the lowest pH and the highest conductivity. Where the two parameters did not agree, the piezometer with the highest conductivity was chosen. Nevertheless, most centerline piezometers do contain the lowest pH and highest conductivity and, thus, presumably represent the plume center for Fe, SO_4, Al, etc. The detailed sampling in 1983 (Table A.2) shows however that a piezometer above or below the chosen centerline piezometer may actually contain higher levels of Fe, SO_4, etc. As a result, the simple definition of the centerline introduces some uncertainty in yearly comparisons.

There are also additional causes of uncertainty in the centerline profiles; some also apply to centerplane profiles. First, there are minor vertical variations in the flow system and centerline piezometers may change yearly. Second, the center of the plume may actually pass between two vertically adjacent piezometers in a bundle. Third, changes in analytical procedures and in laboratories (such as in 1983) can lead to false changes on the centerline. Fourth, horizontal spacing of piezometers near the dam of several meters will not allow the definition of a consistent yearly movement on the order of 1 to 2 m/yr. Fifth, as discussed in Section 4.7.2, single-ion profiles will not necessarily display regular movement where the ion is controlled by mineral equilibrium.

In light of these problems, centerline profiles will now be critically examined. Figure 47 contains yearly pH centerline profiles. Inner-core pH around M1 and M20 shows some variation in the range 4.2 to 4.7 because of the lack of solid-phase control. Plateaus representing sub-regions are not usually obvious because of centerline inaccuracies and, perhaps, chemical kinetic effects. However, the plateau for the calcite sub-region (outer zone) is obvious from about M9 outwards. The plateau is not horizontal and there is an obvious yearly pH decrease, all resulting from gradational solubility in the calcite-siderite solid solution (Morin and Cherry, in review). There is an average movement of the pH front of 1 to 2 m/yr, with movement decreasing as the front moves into an area of slower groundwater movement around M9. There is no retrograde movement of the pH front as observed for Fe and SO_4 (below), because of the unique role of H_3O^+ (and OH^-) in aqueous solutions.

The Fe centerline profile (Figure 48) and SO_4 centerline profile (Figure 49) show a reverse trend to pH. Fe and SO_4 are generally constant or decrease somewhat through the inner core, then decrease sharply through the neutralization zone with some evidence of plateaus, then generally stabilize with some decrease through the calcite sub-region. As with pH, there is a general yearly change in concentrations in the calcite sub-region because of gradational change in solubility in the calcite-siderite solid solution. In other words, the entire calcite sub-region is gradually becoming the siderite sub-region independent of a contaminant front. Both Fe and SO_4 fronts in 1984 display significant retrograde movement, because of the incorrect examination of single-ion trends for ions affected by precipitation-dissolution (Section 4.7.2).

For ions such as Fe, log SI profiles of relevant minerals such as siderite should be examined for movement. Figure 50 shows that there is no retrograde movement between 1980 and 1984, although the 1982 profile displays erratic movement perhaps because of incorrect choices of centerline piezometers. Log SI $Al(OH)_3$ does not show clear trends because of variable crystallinity, the formation of other Al-OH minerals, and probable allophane precipitation.

Figure 51 contains the centerline profiles for Ra-226. For 1979 to 1981, concentration (radioactivity) at M1 is relatively constant and average forward movement of the Ra front is apparent. In 1982 to 1984, concentrations at M1 are about 1/3 less, causing an apparent retrograde movement. Between 1982 and 1983, there is again forward movement then retrograde movement in 1984. This complexity does not allow a quantitative evaluation of a migration rate for the Ra front. The outer zone consistently shows concentrations less than 5 pCi/L on the centerline.

In the far centerline (outer zone), there are theoretically no major geochemical reactions in operation and, thus, only a gradual slope in concentration should be noticeable as was seen closer to the dam. Also, yearly concentration increases are expected as noted closer to the dam. Figure 52 indeed shows the general yearly concentration increase (decrease for pH). However, the unidentified geochemical "trap" at M13, affecting many ions, causes an increase in slope through time.

Log SI profiles (Figure 53) show a variable but generally increasing value through time. Because there is no major change in log SI's at M13, the geochemical trap may simply be an artifact of examining single-ion trends as was the retrograde movement of Fe noted closer to the dam.

5. CONCLUSIONS

This report has presented the 1983 and 1984 geochemical study of the acidic contaminant groundwater plume in Seepage Area A of the Nordic Main uranium-tailings impoundment. The objectives of this study were: 1) collect and evaluate 1984 aqueous geochemical data, 2) conduct detailed tests on the quality of 1984 data, and 3) compare 1983 and 1984 data with past years. The 1983 data were collected by Nand Dave, Tjoe Lim, and Yvonne Boucher of the Elliot Lake Laboratory of CANMET. The 1984 data were collected as part of this study. This report and Morin (1983) contain all data on Nordic Main seepage.

The 1984 field study followed the pattern established by Morin (1983): an average of three piezometers in each centerplane bundle were sampled and all important parameters were measured. In the 1983 study, all piezometers were sampled, but not all important parameters were measured. The ion profiles from 1979-1982 data and from 1984 data are close in outline to the more detailed 1983 profiles, thereby indicating that all piezometers in each bundle need not be sampled.

In this report major emphasis was placed on providing extensive details of field procedures and on quality of geochemical data. Data quality was determined through replicates: seven replicates each from five piezometers. Three of the seven replicates were delivered to the Process and Development Laboratory of Rio Algom Limited. Two duplicates each were delivered to Guelph Chemical Laboratories and to the Elliot Lake Laboratory of CANMET. Results of replicate analyses were examined by several methods, such as Coefficient of Variation (for total precision) and ANOVA (for general accuracy). Methods indicate that precision and accuracy are variable among major ions, minor ions, heavy metals, and radionuclides. Choice of analytical methods and experience in analyzing similar water apparently have an effect on precision and accuracy.

The 1983 and 1984 profiles were compared to past profiles in order to evaluate plume outline, changes in concentrations, and plume movement. Plume outline has generally changed little, although 1984 concentrations were generally lower. Also, because the 1984 study was conducted in late Autumn rather than Summer, the water table and rates of infiltration were higher, resulting in distortion of the plume at the water table. Plume movement is generally consistent with past years and simulations: 1 to 2 m/yr for the $Al(OH)_3$ and siderite sub-regions and about 10 m/yr for the calcite sub-region. However, Fe, SO_4, and a few other ions actually show retrograde movement of their concentration front in 1984. This movement is the result of incorrectly examining single-ion profiles for ions involved in precipitation-dissolution reactions. In these cases, log SI profiles should be examined for movement rather than single-ion profiles. Log SI profiles for siderite (in place of Fe) do show forward movement. The one-dimensional profiles through the center of the plume have more uncertainties than realized in the past, but they can still be used to detect plume movement.

6. RECOMMENDATIONS

Because the 1984 investigation is not an independent study but one facet of an extensive study, some of the following recommendations relate to the entire Nordic study.

1. As discussed in Chapter 3, the physical condition of the piezometers is deteriorating and requires remedial work. The piezometer network will remain useful for an estimated two years. Alternatives for remedial work are discussed in Chapter 3.

2. The unexplained geochemical "trap" at M13 should be investigated in more detail. This trap may be a previously unidentified control on contaminant migration at neutral pH.

3. Buckles Creek was examined physically and chemically in 1982. This study would form the basis of an impact study on Buckles Creek, examining effects on surface water of increasing contaminant concentrations in the groundwater. The seepage collection ditch should also be studied in light of the variation noted in 1984.

4. Because the Nordic Main tailings porewater and the seepage form a complete hydrogeologic system, the tailings and seepage should be sampled simultaneously for a better understanding of trends and changes. The tailings porewater was not sampled in 1984.

5. The major flaw in understanding and simulating contaminant behavior in uranium tailings water is the lack of current knowledge on the calcite-siderite solid solution. While theoretical and experimental studies are underway, results will not be available for years. As a substitute, an empirical equation based on field-study results can be formulated. Placing this equation in the ADNEUT programs would allow more reliable simulations of the calcite and siderite sub-regions.

6. Past simulations with the ADNEUT programs only addressed average yearly movement. The effects of short-term seasonal fluctuations were not explored because of

the lack of field data. With the 1984 results, seasonal fluctuations can now be examined.

7. In this 1984 study, dissolved U, dissolved Th, and dissolved Ra-226 were the only radionuclides examined for precision and accuracy. A study should be undertaken examining the reliability of analyses for individual isotopes of U and Th in uranium-tailings water.

8. Because of relatively low concentrations of U and Th that are encountered in some studies, methods with greater reliability and a lower detection limit should be developed.

9. A major problem of the Nordic Main and Nordic West Arm study is the overwhelming abundance of data. These data are in the possession of the Elliot Lake Laboratory of CANMET, the University of Waterloo, the National Uranium Tailings Program, Morwijk Enterprises, and Golder Associates. An estimated 50% of these data have never been compiled, examined, and compared. Currently, the time required for compiling and plotting data precludes extensive examination and publication of findings. Because the CANUT database is reportedly not capable of addressing all types of hydrogeologic and geochemical data, an independent database is recommended for the Nordic study. Although most of the data are not exchanged between some of the aforementioned organizations, Morwijk Enterprises has been assured access to most or all of the data for the construction of a database.

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Laboratories and personnel

Process Development Laboratory [PDL]
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Table 2
Letter requesting analyses

The accompanying large bottles contain water samples acidified with HCl to a pH of about 1.5. Please analyze for the following. The samples in the small bottles are unacidified and are for Cl analysis only. [The numbers in brackets are approximate concentrations in ppm.]

Ca,Mg,K,Na [400,20,80,200]
Fe,Mn,Co,Cu,Zn,Ni,Pb [3000,20,2,0.04,0.1,1,0.2]
SiO2 [20]
SO4 [9000]
Cl [10]
NH3 [20]
NO3 [2]
Total uranium [0.003 to 1]
Total thorium (x-ray method preferably) [0.04]
Radium-226 [3 to 150 pCi/L]

Please enclose with the results of analyses a brief description of the method used to analyze each species (one or two sentences only), the frequency of calibration for each method, and the precision for each method.

Send results and details on methods to:

Kevin Morin
Morwijk Enterprises
557A King Street East,
Kitchener, Ontario N2G 2L9
(519) 742-3090

Table 3

Methods and accuracy for each laboratory

(copies of letters received in response to the letter in Table 2)

Rio Algom Limited

RIO ALGOM PROCESS & DEVELOPMENT LABORATORY

1985 01 29

Dr. Kevin Morin
Morwijk Enterprises
557 A King St. East
Kitchener, Ontario
N2G 2L9

Dear Sir:

Following is a brief description of methods, frequency of calibration and the precision for each method as per your request. Please accept our apologies for not forwarding this information to you before this date.

1. Al, Ca, Na, K, Mg, Mn, Co, Zn, Ni, Pb - These elements were determined by Atomic Absorption. Where necessary, the samples were diluted to a final concentration of 5-10 ppm. Standards and samples are made to a final volume of 5% HCl. For all analysis, the instrument is calibrated before each series of samples run, and calibration is checked every fifth sample. All standard solution values are verified by the analysis of lab control samples and standard ore samples. Precision for this method is ±10% - 20% for low values (below0.2ppm) and ±5% for higher values.

2. SiO_2 - Gravimetric Method - The silica is dehydrated using perchloric acid and weighed as SiO_2. The method is checked by using lab control samples and standards. Precision for samples is ±10% - 20%.

3. So_4 - Gravimetric Method - The So_4 is precipitated as $BaSO_4$ in a 10% HCl medium. Method is checked using lab control ore samples and standards. Precision for method is ±5%.

4. Cl - A known concentration of silver is added to the sample forming silver chloride complex. The excess silver is determined by Atomic Absorption and the chloride content calculated from this determination. The instrument is calibrated as in number 1, the method is checked by carrying standards of equal concentration as the samples through the complete procedure. Precision for method ±5%.

.../2

5. U_3O_8 - The uranium is separated from the impurities by extraction into Ethyl Acetate. The uranium is leached from the solvent with water and the concentration is determined by the fluorimetric analysis. Standards covering the concentration range of samples are carried through the complete procedure with each batch of samples run. For low values (10 ppb-20 ppb), the precision is ±10% - 20%. For higher values, ±5%.

6. NH_3 - Specific Ion Electrode - A 25/100 dilution was made on all samples, sodium hydroxide is added to the sample to release the ammonia and the concentration is measured by the electrode. Standards covering the concentration of the samples are run before each batch and checked every 10th sample throughout the analysis. Precision is ±5%.

7. Fe - Volumetric Method - The iron is reduced to the ferrous state using stannous chloride. The total iron concentration is then determined by oxidation with potassium dichromate as titrant. The method is checked before analysis using laboratory control ores and standard ores. Precision is ±5%.

8. Ra^{226} - Deamination Method - The radium from the sample is co-precipitated with $BaSO_4$, the barium-radium sulphate is decomposed by fanning with phosphoric acid and taken into solution with dilute HCl. After a suitable growing time, the radon is removed by aeration and counted by a scintillation counting technique.

   The method is checked by running frequent standards and the precision is ±10%.

9. Thorium - Determined by x-ray. I believe that Mr. Nipius has informed you that this determination is not precise at the low level content of thorium in your samples.

I trust this is the information you require. Please call if you need further information.

Yours sincerely,

Bob Patterson
Senior Analyst

BP/lc

GCL Guelph Chemical Laboratories Ltd.
246 Silvercreek Parkway N., Guelph, Ontario, Canada. N1H 1E7 Tel. (519) 836-2313

January 30, 1985

Dr. Kevin Morin
Morwijk Enterprises
557A King St. East
Kitchener, Ontario
N2G 2L9

Dear Dr. Morin:

Re: Method of Analysis and QA/QC

(A) Non-metals

i) Cl

Mercuric nitrate method was used to measure Cl concentration

Standard deviation = 3.3%
Relative error = 2.9%

ii) NO_3

Brucine method was used to measure NO_3 concentration

Standard deviation = 8.15%
Relative error = 4.5 %

iii) SiO_2

Molybdo silicate method was used - employing spectrophoto meter at 410 nm.

Standard deviation = 7.7%
Relative error = 9.8%

iv) NH_3-N

Phenate method was used employing spectrophoto meter at 630 nm.

Standard deviation = 13%
Relative error = 5%

(.....2)

GCL
Guelph Chemical Laboratories Ltd.
246 Silvercreek Parkway N., Guelph, Ontario, Canada. N1H 1E7 Tel. (519) 836-2313

January 30, 1985
Page 2

v) SO_4

Trubidimetric method was used. The error limit = 10%

For the determination of above parameters, the QC progam at Guelph Chemical Labs. included the following:

- Check on calibration standard was made on each of 5 samples analyized.
- sample absorbance measured within the intrapolation region of the standard curve.
- stock solutions were freshly prepared.
- distilled and deionized water were used throughout the investigation.
- melter single pan analytical balance was used for weighings. The balance was checked against standard weights.
- highly resistant borosilicate glass by corning were used.
- ACS analytical reagent grade materials were used in the preparation of standard solutions.

(B) Metal analysis

Metal analysis was accomplished by atomic absorption spectrometry. All standards used for metal analysis were prepared from ACS reagent and were checked against commercial standards obtained from Fisher scientific and BDH. The stocks were prepared in distilled and deionized water.

For each metal analysis the following tests were performed:

- One mid point standard every 5 samples.
- One set of duplicate analysis.
- One reference sample to provide an independant check on the analytical system.

Yours Sincerely,

Raj N. Pandey PhD Queens
General Manager

sh
cc

Energy, Mines and Resources Canada
Énergie, Mines et Ressources Canada

Science and Technology
Science et Technologie

Your file Votre référence

Our file Notre référence
C 025-1

February 13, 1985

Dr. K. Morin
Morwijk Enterprises
557A King St. E.
Kitchener, Ontario
N2G 2L9

Dear Kevin:

Enclosed are two sets of data; one for the 1984 M-series samples you gave me and the other is the corrections for magnesium during the 1983 M-series plume study. Some results were questionable so Co, Cl^-, NO_3^{2-} and Ra-226 will be repeated.

The following elements (Mg, U, Si, Cu, Ni, Th, Pb, Ca, Fe, Mn, Al) are all analysed using a Beckman SpecSpan V. This is a D.C.P. (direct current plasma) instrument. After every five samples are analysed, a set of high and low standards are inserted. If a 3% difference in reading occurs from the previous standards, the instrument is repeaked and recalibrated. For elements such as Th,Pb, Co, Ni and U, the detection limit of that element had to be found. These are the detection limits for the following elements:

Thorium	1.0 mg/ℓ
Lead	0.1 mg/ℓ
Uranium	0.8 mg/ℓ
Ni	0.1 mg/ℓ
Co	0.3 mg/ℓ

Chloride, nitrate and sulphate are analysed using a Dionex H.P.I.C. Standards are inserted after every five samples. The maximum concentration of mixed standards used in our H.P.I.C. AS-4 anion column is 50 mg/l SO_4^{2-}, 20 mg/l NO_3^{2-} and 4 mg/l Cl^-. To bring sulphate into the 50 mg/l range a 1000 x dilution is done. However, this dilution factor causes the Cl^- and NO_3^{2-} results to be low and inaccurate. If a 100 x dilution is made to fit Cl^- and NO_2^- into the range the SO_4^{2-} would be overranged and the high iron content could damage our AS-4 anion column even if the sample is prefiltered and a guard column is used. As you can see we have encountered some problems with the anions.

.../2

Elliot Lake Laboratory,
Mining Research Laboratories
Canada Centre for Mineral
and Energy Technology,
P.O. Box 100,
Elliot Lake, Ont.
P5A 2J6

Laboratoire d'Elliot Lake
Laboratoires de recherche minière,
Centre canadien de la technologie
des minéraux et de l'énergie,
Case Postale 100,
Elliot Lake, Ont.
P5A 2J6

In order to conserve energy and resources, this paper contains 45 per cent recycled post-consumer fibre.

A des fins de conservation de l'energie et des ressources ce papier contient 45 pour cent de fibres recyclées.

If there are any questions regarding the results of any one of the samples please do not hesitate to call me at work.

Yours sincerely,

Yvonne Boucher

Yvonne Boucher

YB/csj

ME

Morwijk Enterprises
557A King Street East
Kitchener, Ontario N2G 2L9

The Ra-226 analyses on GCL samples were performed by the Department of Chemistry at the University of Waterloo. The following details on the analysis were provided by the analyst, Barry Hauch.

Aqueous Ra-226 analyses are performed by the indirect counting method. Ra is removed from the sample by an exchange column and isolated. After a period of several days to weeks, the activities of Ra-226 daughters are counted and the activity of Ra-226 is then calculated. Precision of this method is reported at 3% at the 95% confidence level. Accuracy (relative error) is -2%.

K.M.

Table 4

Means and standard deviations for all replicates
(concentrations are ppm, except pCi/L for Ra-226)
(Ra-226 analyses for GCL were performed by UW)

M1-7	Mean	Std Dev	n		Mean	Std Dev	n
Fe				Ca			
PDL	4952.00	30.05	3		419.67	11.01	3
GCL	5155.00	530.33	2		319.00	11.31	2
CAN	5117.00	46.67	2		563.95	40.09	2
Mg				Na			
PDL	305.67	0.57	3		10.67	0.57	3
GCL	146.50	3.54	2		4.20	0.57	2
CAN	364.00	1.41	2		-	-	0
K				Mn			
PDL	89.67	4.73	3		19.67	0.57	3
GCL	46.50	0.71	2		18.40	0.28	2
CAN	-	-	0		40.40	1.13	2
Al				Cu			
PDL	81.33	1.15	3		0.02267	0.010	3
GCL	70.50	2.12	2		0.50	0.453	2
CAN	84.06	0.07	2		0.039	0.0	1
Co				Zn			
PDL	3.033	0.058	3		0.2267	0.006	3
GCL	4.00	0.00	2		0.305	0.021	2
CAN	4.18	0.042	2		-	-	0
Pb				Ni			
PDL	0.29	0.036	3		1.8	0.00	3
GCL	0.75	0.21	2		2.3	0.28	2
CAN	1.04	1.43	2		2.15	0.04	2
SO4				SiO2			
PDL	10974.33	53.16	3		7.33	7.09	3
GCL	13750.50	946.82	2		49.90	3.96	2
CAN	12379.50	726.20	2		13.35	0.73	2
Cl				NH3			
PDL	11.23	4.99	3		35.367	2.29	3
GCL	14.80	1.70	2		13.90	0.85	2
CAN	38.75	25.67	2		-	-	0
NO3				Ra-226			
PDL	-	-	0		71.67	7.02	3
GCL	3.7	0.99	2		270.10	16.40	2
CAN	-	-	0		77.79	2.12	2
Th				U			
PDL	-	-	0		0.1945	0.0298	2
GCL	-	-	0		-	-	0

```
CAN *    0.0       0.0      2     1.092        0.003     2
```

M2-2

Fe				Ca			
PDL	2318.67	17.79	3		544.67	21.73	3
GCL	2249.50	132.23	2		408.00	199.40	2
CAN	2346.00	18.38	2		687.55	40.09	2
Mg				Na			
PDL	313.33	4.16	3		38.00	1.00	3
GCL	193.00	175.36	2		34.15	3.32	2
CAN	388.50	10.61	2		-	-	0
K				Mn			
PDL	118.67	4.04	3		15.00	0.00	3
GCL	126.00	5.66	2		15.50	0.28	2
CAN	-	-	0		30.9	0.14	2
Al				Cu			
PDL	0.05*	0.00	3		0.063	0.006	3
GCL	0.33	0.00	2		0.055	0.035	2
CAN	0.382	0.19	2		0.027	0.0	1
Co				Zn			
PDL	1.00	0.00	3		0.056	0.003	3
GCL	1.90	0.50	2		0.06	0.057	2
CAN	1.30	0.028	2		-	-	0
Pb				Ni			
PDL	0.173	0.038	3		0.34	0.015	3
GCL	0.06	0.00	2		0.75	0.495	2
CAN	0.884	0.112	2		0.434	0.022	2
SO4				SiO2			
PDL	6456.00	150.91	3		5.33	0.577	3
GCL	8080.50	1201.37	2		30.55	3.465	2
CAN	7624.00	434.16	2		18.39	0.509	2
Cl				NH3			
PDL	60.267	0.38	3		51.467	2.03	3
GCL	34.35	22.42	2		37.7	3.96	2
CAN	84.45	66.13	2		-	-	0
NO3				Ra-226			
PDL	-	-	0		2.33	0.577	3
GCL	2.90	0.85	2		17.94	2.390	2
CAN	-	-	2		0.185	0.262	2
Th				U			
PDL	-	-	0		-	-	0
CAN	0.0*	0.0	2		0.4*	0.0	2

* = all values below detection, therefore std dev=0

M14-2

Fe				Ca		
PDL	60.33	3.79	3	277.00	6.93	3
GCL	958.50	1269.25	2	393.00	178.19	2
(GCL	82.00	29.70	re-analysis)			
CAN	65.15	3.32	2	358.45	35.71	2
Mg				Na		
PDL	72.00	0.00	3	35.33	0.58	3
GCL	208.50	204.35	2	37.65	8.70	2
CAN	86.45	1.20	2	-	-	0
K				Mn		
PDL	3.63	0.15	3	4.00	0.00	3
GCL	71.00	94.75	2	3.60	0.00	2
(GCL	4.05	0.07	re-analysis)			
CAN	-	-	0	5.20	0.01	2
Al				Cu		
PDL	0.05*	0.00	3	0.003	0.001	3
GCL	0.145	0.02	2	0.045	0.021	2
CAN	0.32	0.05	2	0.011	0.0	1
Co				Zn		
PDL	0.017	0.020	3	0.002	0.002	3
GCL	0.003*	0.00	2	0.007	0.005	2
CAN	0.15*	0.00	2	-	-	0
Pb				Ni		
PDL	0.005*	0.00	3	0.022	0.014	3
GCL	0.45	0.21	2	0.304	0.419	2
CAN	0.079	0.04	2	0.05	0.0	2
SO4				SiO2		
PDL	547.67	426.16	3	8.00	4.58	3
(PDL	838.33	154.22	re-analysis)			
GCL	829.50	313.25	2	6.70	1.27	2
CAN	956.45	0.92	2	17.48	0.13	2
Cl				NH3		
PDL	73.57	1.82	3	2.05	0.15	3
GCL	68.00	5.66	2	4.05	0.49	2
CAN	125.85	36.98	2	-	-	0
NO3				Ra-226		
PDL	-	-	0	1.67	0.57	3
GCL	0.00	0.00	2	2.94	0.91	2
CAN	-	-	0	0.00*	0.00	2
Th				U		
PDL	-	-	0	0.002	0.001	3
GCL	-	-	0	-	-	0
CAN	0.0	0.0	2	0.04	0.0	2

* = all values below detection, therefore std dev=0

M24-5

Fe				Ca		
PDL	3224.33	30.62	3	421.00	9.17	3
GCL	3374.50	265.17	2	442.00	4.24	2
CAN	3265.00	14.14	2	529.70	30.26	2
Mg				Na		
PDL	245.00	1.00	3	22.33	0.58	3
GCL	244.50	19.09	2	9.15	10.39	2
(GCL			re-analysis	16.25	0.35)	
CAN	300.50	4.95	2	-	-	0
K				Mn		
PDL	100.33	2.08	3	14.33	0.57	3
GCL	110.50	3.54	2	15.00	0.14	2
CAN	-	-	0	30.50	0.85	2
Al				Cu		
PDL	4.367	0.115	3	0.0075	0.004	3
GCL	4.600	0.141	2	0.415	0.545	2
CAN	6.355	0.162	2	-	-	0
Co				Zn		
PDL	1.9	0.00	3	0.094	0.004	3
GCL	2.9	0.00	2	0.09	0.014	2
CAN	2.47	0.028	2	-	-	0
Pb				Ni		
PDL	0.15	0.03	3	1.13	0.058	2
GCL	0.6	0.04	2	1.6	0.42	2
CAN	1.13	0.04	2	1.37	0.04	2
SO4				SiO2		
PDL	7423.67	12.67	3	2.00	1.73	2
GCL	8389.50	371.23	2	25.1	2.83	2
CAN	8445.50	190.21	2	11.795	0.39	2
Cl				NH3		
PDL	33.60	2.82	3	41.13	0.58	3
GCL	9.25	3.61	2	25.35	7.14	2
CAN	62.60	5.23	2	-	-	0
NO3				Ra-226		
PDL	-	-	0	12.67	0.57	3
GCL	2.80	0.99	2	48.85	1.63	2
CAN	-	-	0	15.7	1.70	2
Th				U		
PDL	-	-	0	-	-	0
CAN	0.0*	0.0	2	0.4*	0.0	2

* = all values below detection, therefore std dev=0

M25-7

	Fe			Ca		
PDL	1946.33	20.21	3	323.67	4.73	3
GCL	2015.00	66.47	2	423.00	11.31	2
CAN	1918.50	10.61	2	396.55	19.73	2
	Mg			**Na**		
PDL	148.00	1.73	3	6.90	0.20	3
GCL	330.50	13.44	2	6.15	1.06	2
CAN	173.00	0.0	2	-	-	0
	K			**Mn**		
PDL	39.67	0.57	3	9.20	0.35	3
GCL	95.50	0.71	2	8.90	0.00	2
CAN	-	-	0	15.70	0.0	2
	Al			**Cu**		
PDL	76.33	0.57	3	0.005	0.004	3
GCL	69.50	2.12	2	0.10	0.057	2
CAN	87.84	0.0	2	0.046	0.0	1
	Co			**Zn**		
PDL	1.37	0.058	3	0.048	0.004	3
GCL	2.05	0.071	2	0.045	0.035	2
CAN	1.65	0.173	2	-	-	0
	Pb			**Ni**		
PDL	0.10	0.03	3	1.13	0.058	3
GCL	1.05	0.21	2	1.40	0.141	2
CAN	0.76	0.008	2	1.425	0.02	2
	SO4			**SiO2**		
PDL	4807.00	107.41	3	5.33	3.79	3
GCL	4666.00	87.68	2	10.90	0.14	2
CAN	5494.00	8.49	2	29.69	0.15	2
	Cl			**NH3**		
PDL	9.43	0.91	3	17.63	0.12	3
GCL	8.80	0.99	2	13.80	0.42	2
CAN	24.30	9.90	2	-	-	0
	NO3			**Ra-226**		
PDL	-	-	0	25.00	1.00	3
GCL	3.40	0.71	2	73.49	6.52	2
CAN	-	-	2	36.1	3.11	2
	Th			**U**		
PDL	-	-	0	-	-	0
CAN	0.05*	0.0	2	0.4*	0.0	2

* = all values below detection, therefore std dev=0

Table 5
Summary of CV values for each piezometer

CV = (Std Dev / Mean) x 100%

TDS = approximate calculated TDS, as an indicator of dilute (<3000) and concentrated (>3000) water

Values below detection limit were set at (detection/2.0)

* = all values are below detection, therefore CV=0
X = only one analysis performed, therefore CV=0

	M1-7			M2 -2			M14-2		
TDS	17000			1000			1300		
Lab	PDL	GCL	CAN	PDL	GCL	CAN	PDL	GCL	CAN
Fe	0.61	10.29	0.91	0.77	5.88	0.78	6.27	132.42	5.10
				Fe re-analysis -->				(36.22)	
Ca	2.62	3.55	7.11	3.99	48.87	5.83	2.50	45.34	9.96
Mg	0.19	2.41	0.39	1.33	90.86	2.73	0.00	98.01	1.39
Na	5.38	13.47	-	2.63	9.73	-	1.63	23.10	-
K	5.27	1.52	-	3.41	4.49	-	4.20	133.45	-
				K re-analysis -->				(1.75)	
Mn	2.92	1.54	2.80	0.00	1.83	0.46	0.00	0.00	0.27
Al	1.42	3.01	0.08	*0.00	0.00	9.63	*0.00	14.63	16.80
Cu	46.26	90.51	X	104.91	64.28	X	43.52	47.14	X
Co	1.90	0.00	1.00	0.00	37.22	2.15	121.17	*0.00	*0.00
Zn	2.53	6.96	-	5.48	94.28	-	98.81	76.15	-
Pb	12.43	28.28	137.40	21.84	0.00	12.65	*0.00	47.14	52.19
Ni	0.00	12.30	2.08	4.45	66.00	5.15	66.56	137.69	0.0*
SO4	0.48	6.89	5.87	2.34	14.87	5.69	77.81	37.76	0.10
			SO4 re-analysis -->				(18.40)		
SiO2	96.79	7.94	5.45	10.83	11.34	2.77	57.28	19.00	0.72
Cl	44.42	11.47	66.24	0.63	65.26	9.63	2.48	8.32	29.39
NH3	6.49	6.10	-	3.95	10.50	-	7.57	12.22	-
NO3	-	26.76	-	-	29.26	-	-	0.00	-
Ra226	9.80	6.07	2.73	24.73	13.32	141.62	34.57	30.79	*0.00
Th	-	-	0.0*	-	-	0.0*	-	-	0.0*
U	88.69	-	4.93	-	-	0.0*	52.62	-	0.0*

		M24-5			M25-7	
TDS		12000			7000	
Lab	PDL	GCL	CAN	PDL	GCL	CAN
Fe	0.95	7.86	0.43	1.04	3.30	0.55
Ca	2.18	0.96	5.71	1.04	3.30	4.98
Mg	0.41	7.81	1.65	1.17	4.07	0.00
Na	2.58	113.60	-	2.90	17.25	-
		(2.18)	<-- Na re-analysis			
K	2.07	3.20	-	1.45	0.74	-
Mn	4.03	0.94	2.78	3.77	0.00	0.00
Al	2.64	3.07	2.56	0.76	3.05	0.00
Cu	57.81	131.21	-	86.72	56.57	c
Co	0.00	0.00	1.13	4.22	3.45	10.52
Zn	4.31	15.71	-	8.61	78.57	-
Pb	20.00	70.71	3.75	30.00	20.20	1.03
Ni	5.09	26.52	3.10	5.09	10.10	1.49
SO4	0.17	4.42	2.25	2.23	1.88	0.15
re-analysis of SO4 -->				(18.40)		
SiO2	86.60	11.27	3.29	71.02	1.30	0.50
Cl	8.38	38.99	8.36	9.62	11.25	40.74
NH3	1.40	28.17	-	0.65	3.07	-
NO3	-	35.36	-	-	20.80	-
Ra226	4.56	3.33	10.83	4.00	8.87	8.61
Th	-	-	0.0*	-	-	0.0*
U	-	-	0.0*	-	-	0.0*

Table 6

Summary of average CV values for each laboratory

Excluding blanks and "*" in Table 5

DILute=M14-2, CONCentrated=all others

Lab	PDL			GCL			CAN		
	TOTAL	CONC	DIL	TOTAL	CONC	DIL	TOTAL	CONC	DIL
Fe	1.93	0.84	6.27	31.95	6.83	132.42	1.55	0.67	5.10
Fe re-analysis -->				(12.71)		(36.22)			
Ca	2.55	2.56	2.50	20.28	14.01	45.34	6.72	5.91	9.96
Mg	0.62	0.78	0.00	40.63	26.29	98.01	1.23	1.19	1.39
Na	3.02	3.37	1.63	35.43	38.51	23.10	-	-	-
Na re-analysis -->				(13.15)		(10.66)			
K	3.28	3.05	4.20	28.68	2.49	133.45	-	-	-
K re-analysis -->				(2.34)		(1.75)			
Mn	2.14	2.68	0.00	0.86	1.08	0.00	1.26	1.51	0.27
Al	1.61	1.61	-	4.75	2.28	14.63	5.81	3.07	16.80
Cu	67.84	73.93	43.52	77.94	85.64	47.14	-	-	-
Co	25.46	1.53	121.17	10.17	10.17	-	3.70	3.70	-
Zn	23.95	5.23	98.81	54.33	48.88	76.15	-	-	-
Pb	21.07	21.07	-	33.27	29.80	47.14	41.40	38.71	52.19
Ni	16.24	3.66	66.56	50.52	28.73	137.69	2.96	2.96	-
SO4	16.61	1.31	77.81	13.16	7.02	37.76	2.81	3.49	29.39
	(4.72	1.31	18.40)	<-- re-analysis of SO4					
SiO2	64.50	66.31	57.28	10.17	7.96	19.00	2.55	3.00	0.72
Cl	13.11	15.76	2.48	27.06	31.74	8.32	30.87	31.24	29.39
NH3	4.01	3.12	7.57	12.01	11.96	12.22	-	-	-
NO3	-	-	-	22.44	28.05	0.00	-	-	-
Ra226	15.53	10.77	34.57	12.48	7.90	30.79	40.95	40.95	-
Th	-	-	-	-	-	-	-	-	-
U	70.66	88.69	52.62	-	-	-	4.93	4.93	-

Table 7

ANOVA and Student t-test results
(see Table 8 for additional details)

ANOVA hypothesis: means reported by all three laboratories are identical

Student t-test hypothesis: means reported by two laboratories are identical

A = hypothesis accepted, R = hypothesis rejected

Confidence levels: 95% and 99%

	M1-7			M2-2			M14-2			M24-5			M25-7		
	Code	A/R		Code	A/R		Code	A/R		Code	A/R		Code	A/R	
		95	99		95	99		95	99		95	99		95	99
Fe	1	A	A	1	A	A	1	A	A	1	A	A	1	A	A
Ca	1	R	R	1	A	A	1	A	A	1	R	R	1	R	R
Mg	1	A	A	1	A	A	1	A	A	1	R	R	1	R	R
Na	2	R	R	2	A	A	2	A	A	2	A	A	2	A	A
K	2	R	R	2	A	A	2	A	A	2	R	A	2	R	R
Mn	1	R	R	1	R	R	1	R	R	1	R	R	1	R	R
Al	1	R	R	1	R	A	1	R	R	1	R	R	1	R	R
Cu	2	A	A	2	A	A	2	R	A	2	A	A	2	A	A
Co	1	R	R	1	A	A	1	X	X	1	R	R	1	A	A
Zn	2	R	R	2	A	A	2	A	A	2	A	A	2	A	A
Pb	1	A	A	1	R	R	1	R	A	1	R	A	1	R	R
Ni	1	R	A	1	A	A	1	A	A	1	A	A	1	R	A
SO4	1	R	A	1	A	A	1	A	A	1	R	R	1	R	R
SiO2	1	R	R	1	R	R	1	A	A	1	R	R	1	R	R
Cl	1	A	A	1	R	A	1	A	A	1	R	R	1	A	A
NH3	2	R	R	2	R	A	2	R	R	2	R	A	2	R	R
Ra-226	1	R	R	1	R	R	1	R	A	1	R	R	1	R	R
U	3	R	A	-	-	-	3	R	R	-	-	-	-	-	-

Codes: 1 = ANOVA test
2 = Student t-test for PDL and GCL data
3 = Student t-test from PDL and CAN data

X = all values were less than detection limit

Table 8
Summary of ANOVA and student t-test results

Percentage of hypothesis acceptance from Table 7
95% and 99% confidence levels

Dilute=M14-2, Concentrated= all others

	Overall		Concentrated		Dilute	
	95	99	95	99	95	99
Fe	100	100	100	100	100	100
Ca	60	60	50	50	100	100
Mg	60	60	50	50	100	100
Na	80	80	75	75	100	100
K	40	60	25	50	100	100
Mn	0	0	0	0	0	0
Al	0	20	0	25	0	0
Cu	80	100	100	100	0	100
Co	50	50	50	50	-	-
Zn	80	80	75	75	100	100
Pb	20	60	25	50	0	100
Ni	60	100	50	100	100	100
SO4	40	60	25	50	100	100
SiO2	20	20	0	0	100	100
Cl	60	80	50	75	100	100
NH3	0	40	0	50	0	0
Ra-226	0	20	0	0	0	100
U	0	50	0	100	0	0

Table 9
Piezometers from bundles representing the centerline

1979	1980	1981	1982	1983	1984
M1-6	M1-6	M1-6	M1-6	M1-6	M1-6
	M20-5	M20-5	M20-5	M20-5	
M8-8	M8-8	M8-8	M8-8	M8-8	M8-8
M16-1.5	M16-2.5 (-3.0 for pH)	M16-2.5	M16-2.5	M16-1.5	M16-2.5
		M24-5			
M17-2.5	M17-2.5 (-3.0 for pH)	M17-2.5	M17-2.5	M17-2.5	M17-2.5
M18-2	M18-2	M18-2	M18-2	M18-2	M18-2
M19-3	M19-2	M19-2	M19-2	M19-2	M19-3
M9-8	M9-6 (-8 for pH)	M9-8	M9-8	M9-6 (-8 is missing)	M9-7
	M27-6	M27-7	M27-7	M27-8	M27-7
M10-7	M10-6	M10-6	M10-6		M10-6
M11-8	M11-7	M11-7	M11-7	M11-7	M11-7
M12-7	M12-8	M12-8	M12-8	M12-7	M12-8
M13-8	M13-8	M13-8	M13-8	M13-8	M13-7
M14-6	M14-7	M14-7	M14-7		M14-6

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37. NH3 profiles along the Centerplane and Far Centerplane for 1984

38. Cu profile along the Centerplane for 1984

39. Co profiles along the Centerplane and Far Centerplane for 1984

40. Zn profiles along the Centerplane and Far Centerplane for 1984

41. Pb profiles along the Centerplane and Far Centerplane for 1984

42. Ni profiles along the Centerplane and Far Centerplane for 1984

43. Ra-226 profiles along the Centerplane for 1983 and 1984

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51. Ra-226 profiles along the Centerline for 1979-1984

52. pH, Fe, and SO4 profiles along the Far Centerline for 1979-1984

53. Log SI calcite, siderite, and amorphous Al(OH)3 along the Far Centerline for 1980, 1982, and 1984

FIGURES

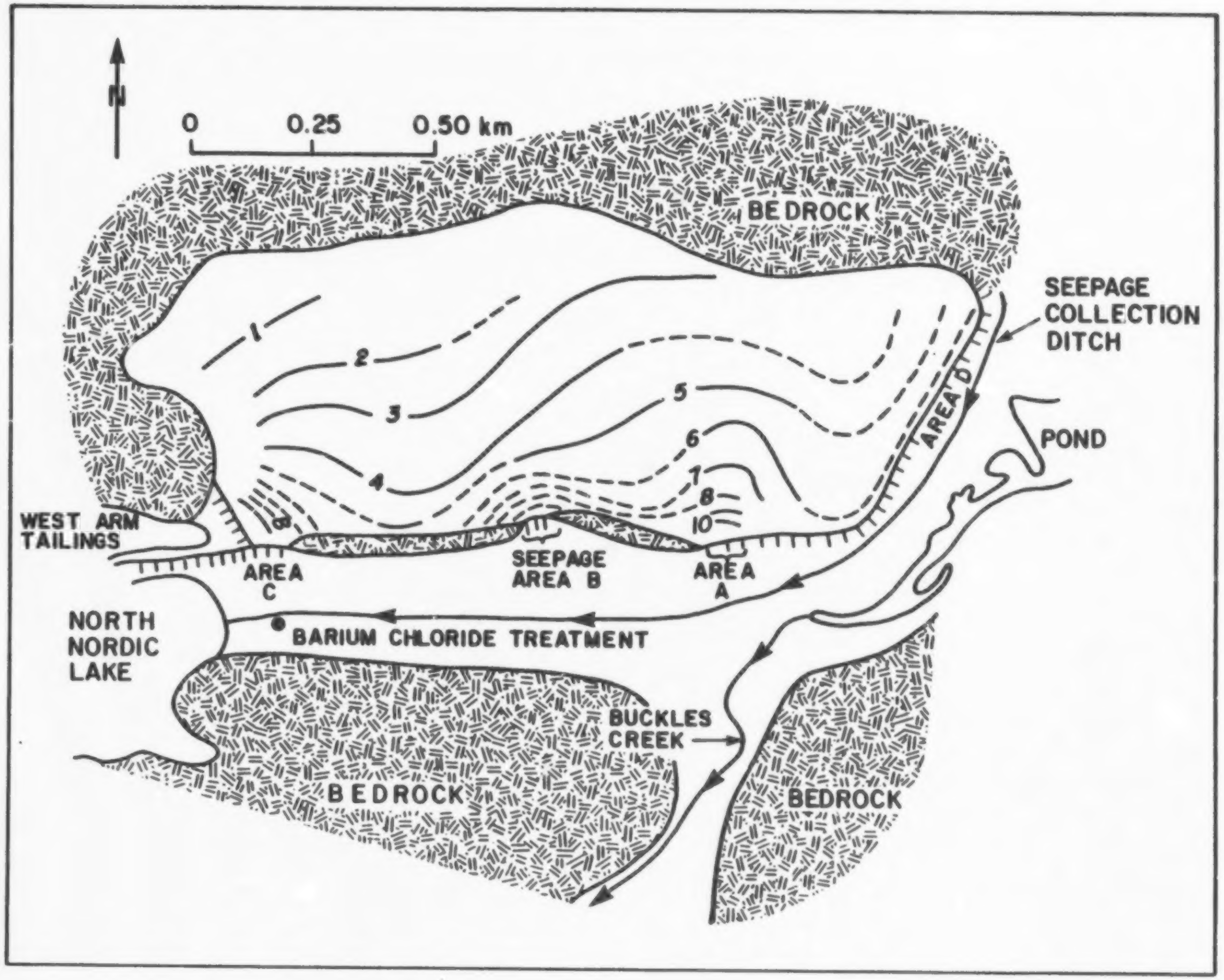


Figure 1. Aerial schematic of the Nordic Main Tailings Area.

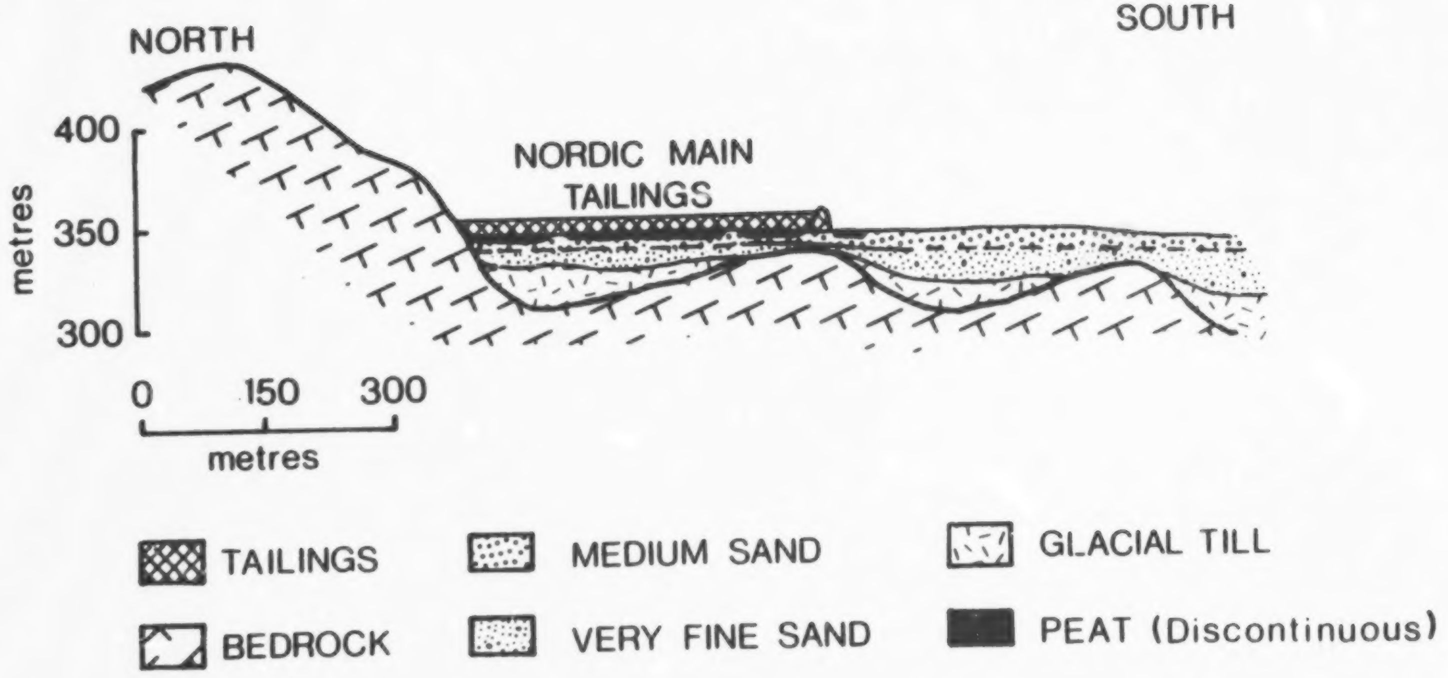


Figure 2. Generalized north-south cross-section through the Nordic Main Area.

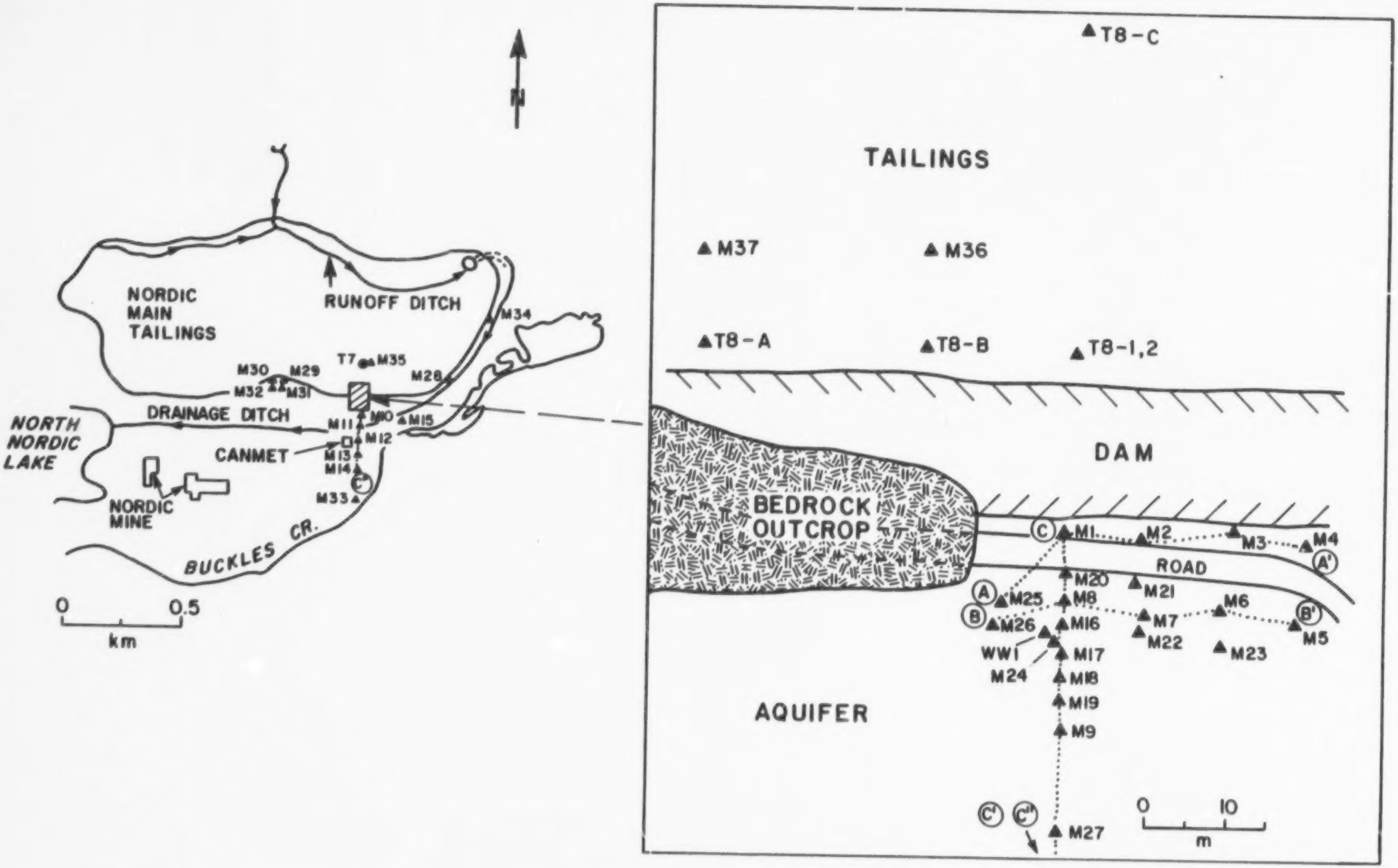


Figure 3. Piezometer locations.

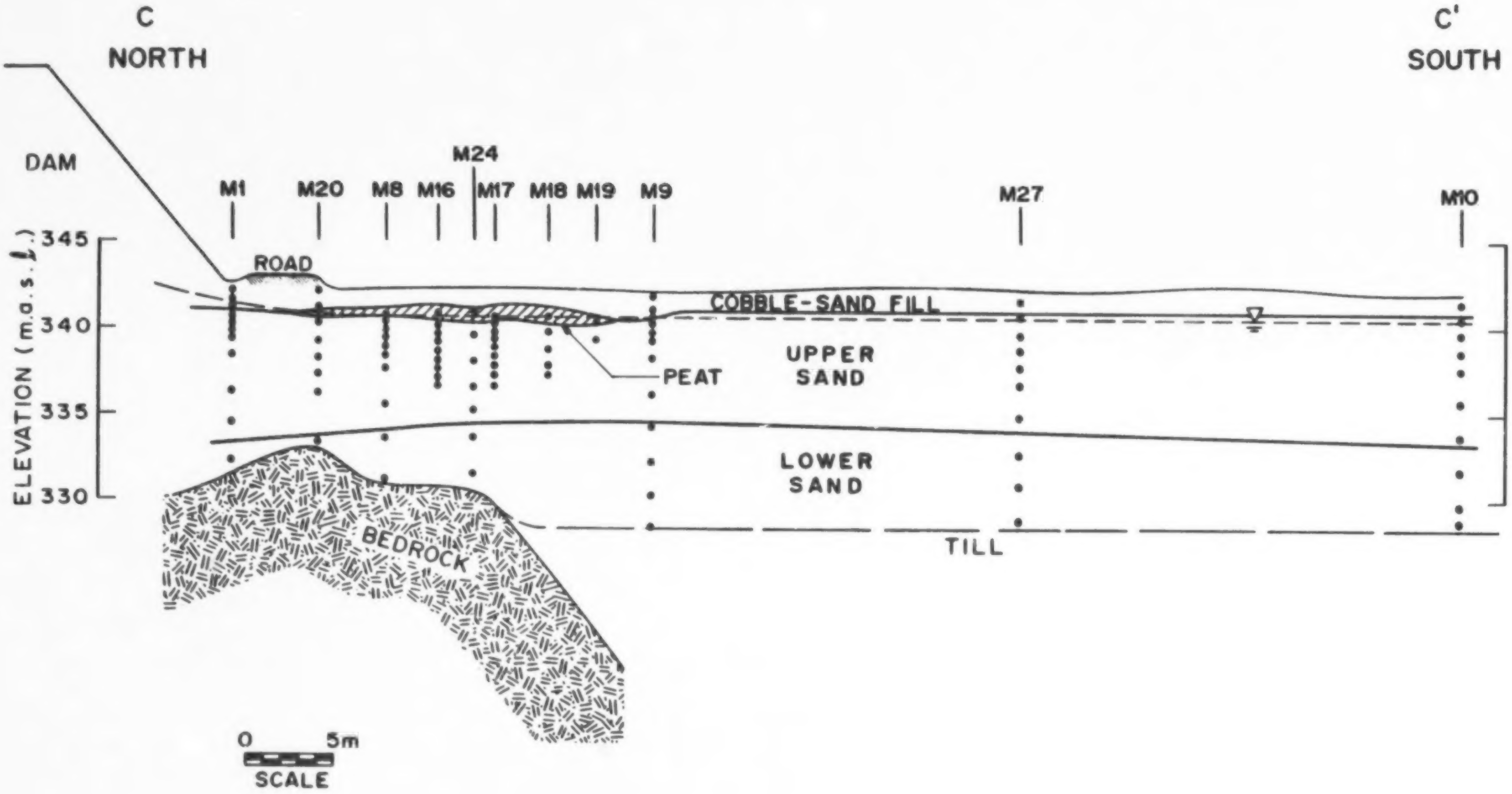


Figure 4. Stratigraphy of Seepage Area A.

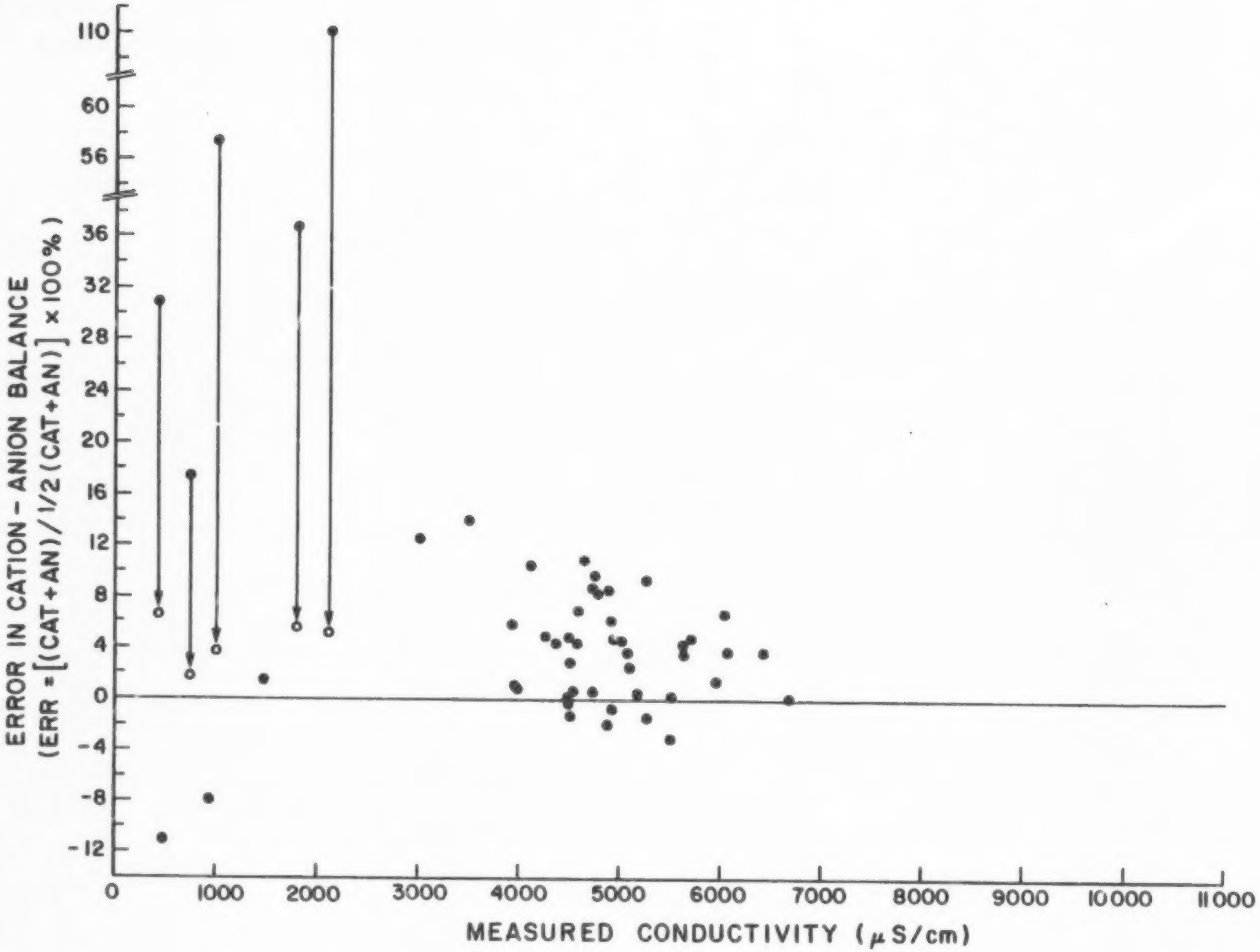
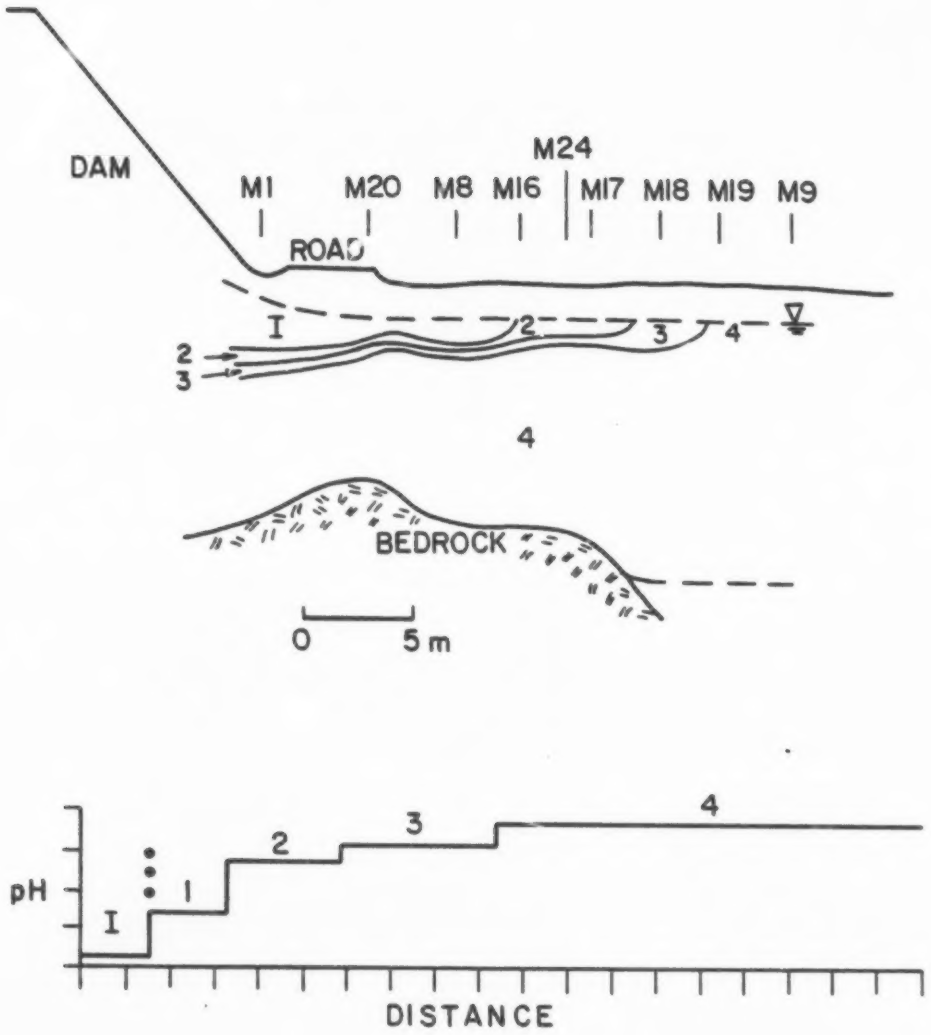


Figure 5. Comparison of field-measured conductivity to error in cation-anion balance.



I = INNER CORE
1 = Fe $(OH)_3$ SUB-REGION AROUND pH 3.5
2 = Al $(OH)_3$ SUB-REGION AROUND pH 5.0
3 = SIDERITE SUB-REGION AROUND pH 5.2
4 = CALCITE SUB-REGION, OR OUTER ZONE, at pH 5.6

Figure 6. Schematic diagram of the sub-region concept with application to Area A.

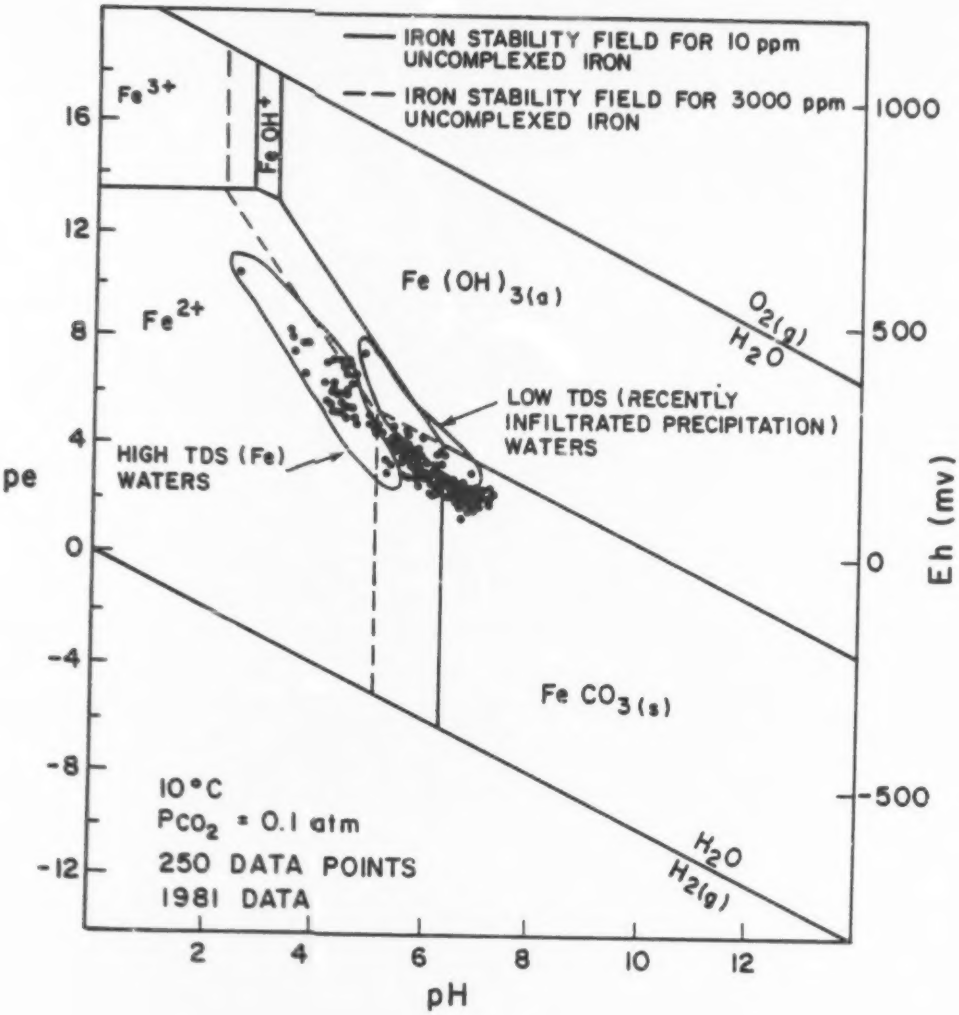


Figure 7. Eh-pH-Fe diagram for Area A.

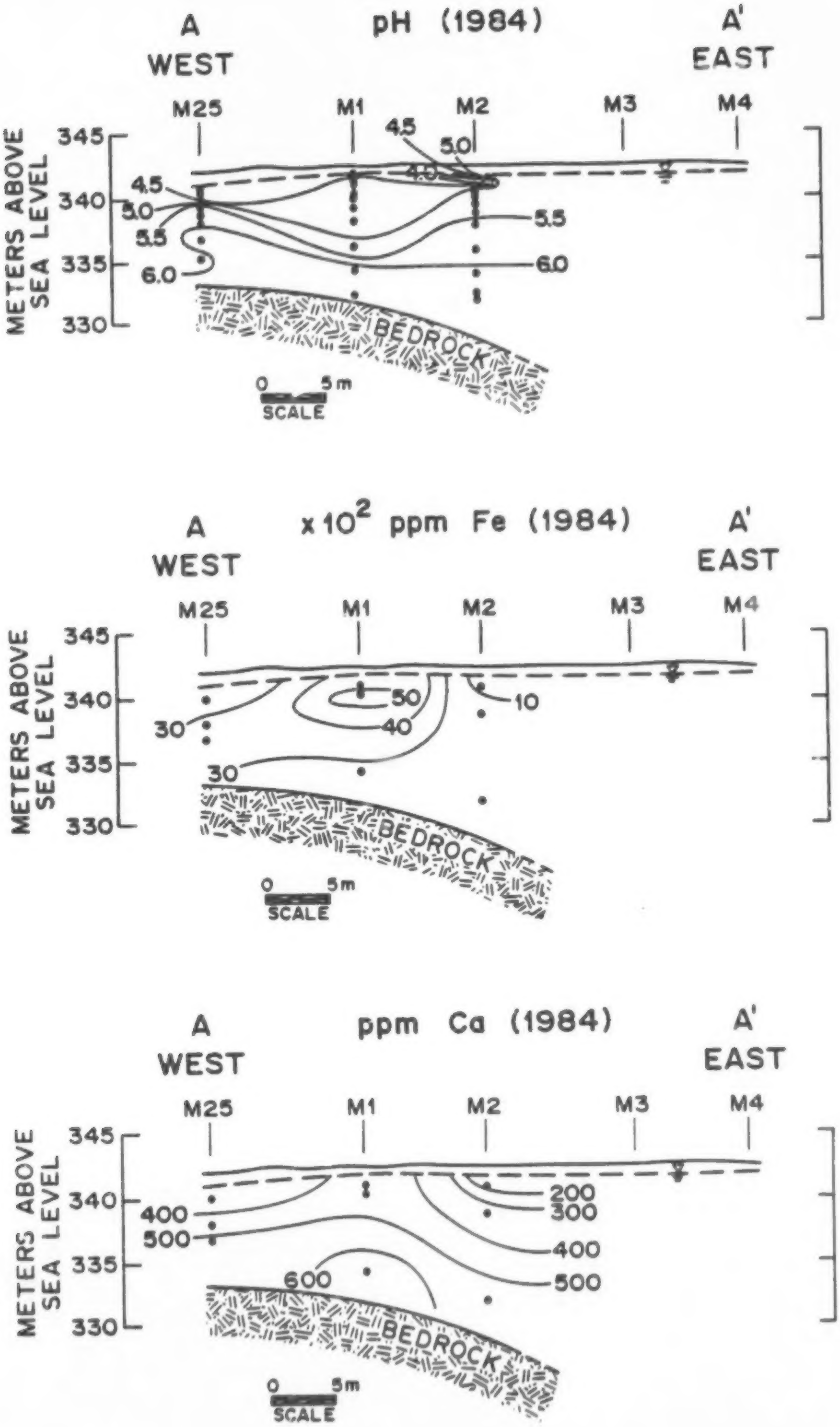


Figure 8. pH, Fe, and Ca profiles along Cross-section A-A' for 1984.

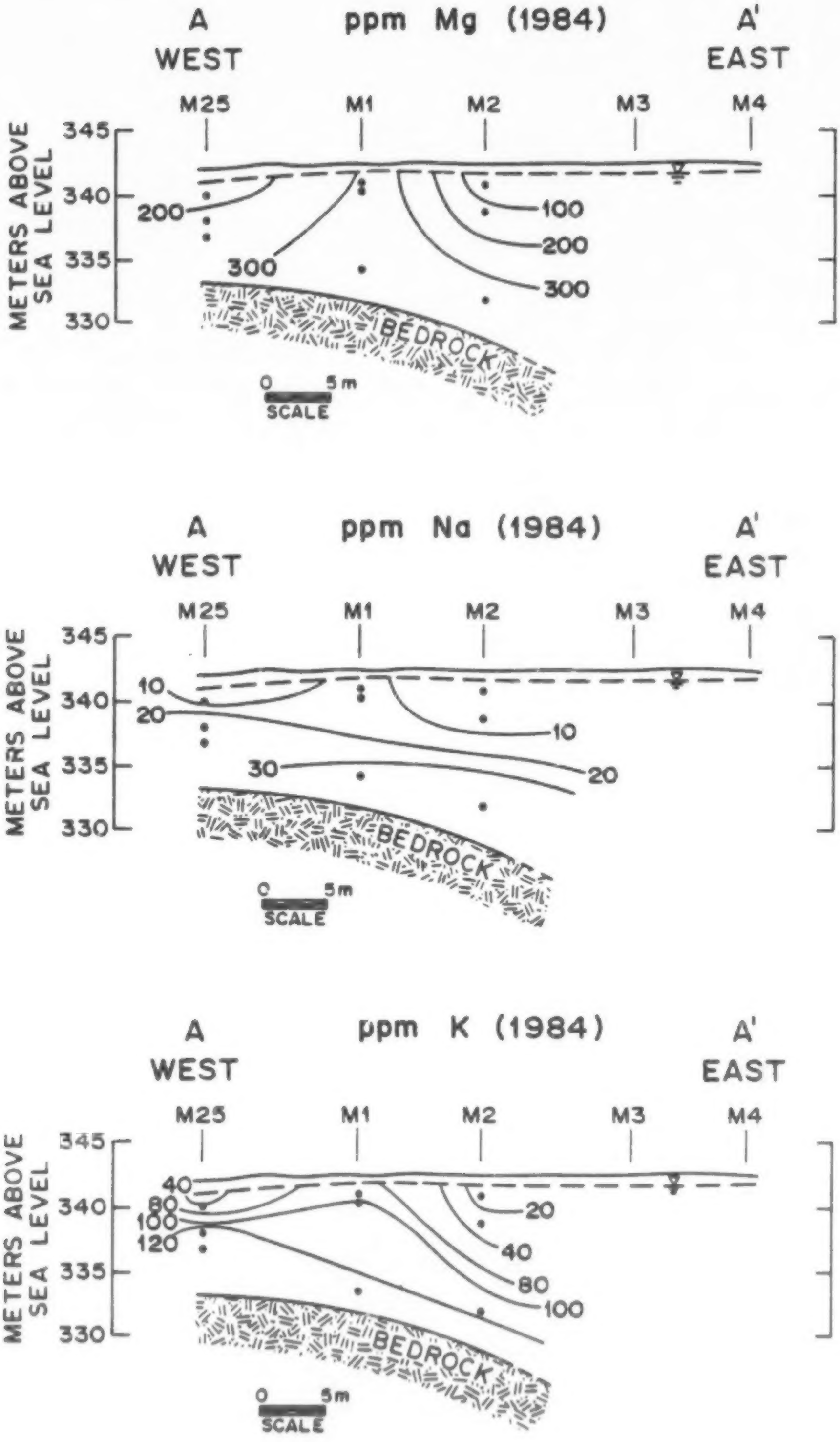


Figure 9. Mg, Na, K profiles along Cs. A-A' for 1984.

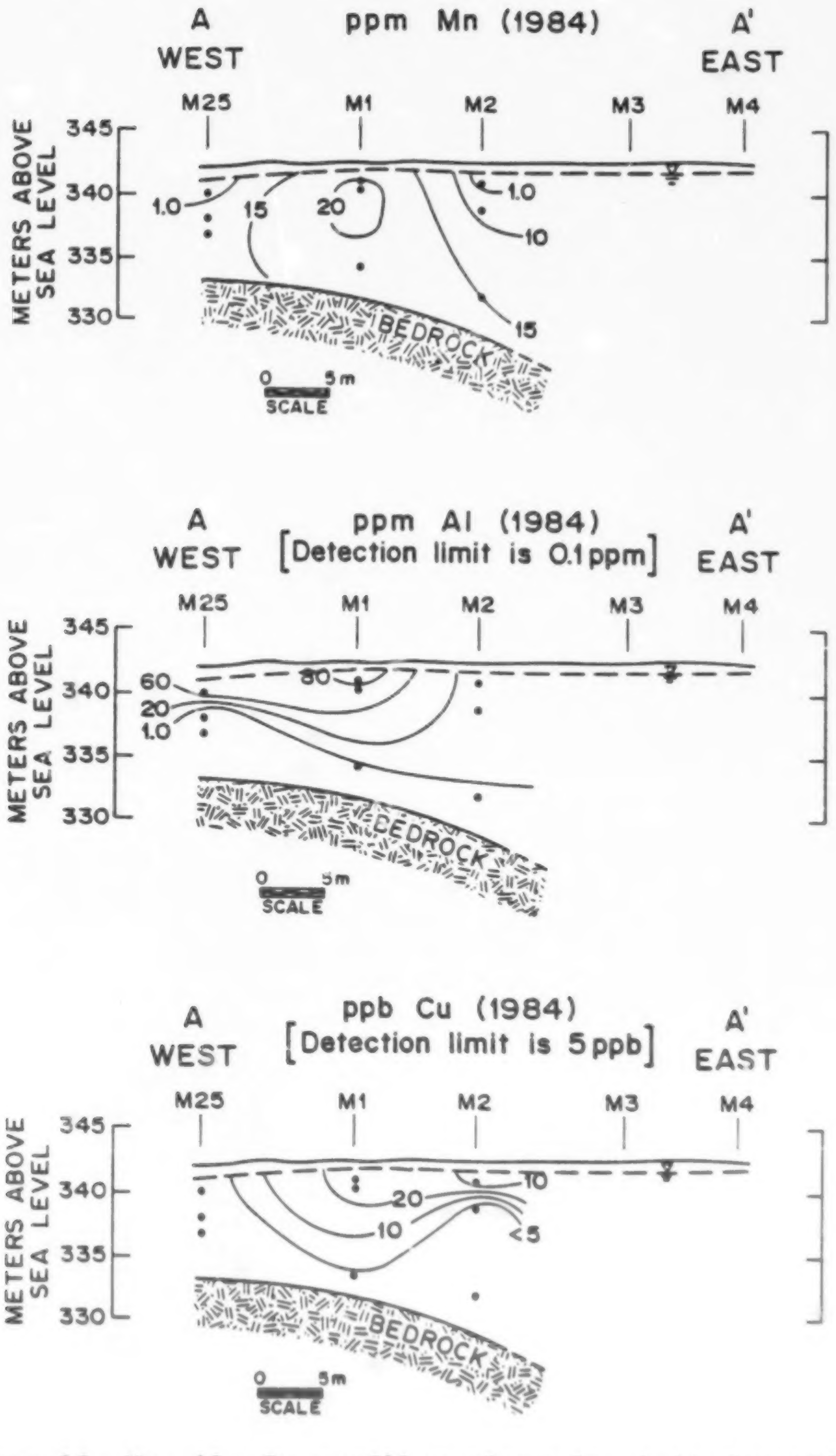


Figure 10. Mn, Al, Cu profiles along Cs. A-A' for 1984.

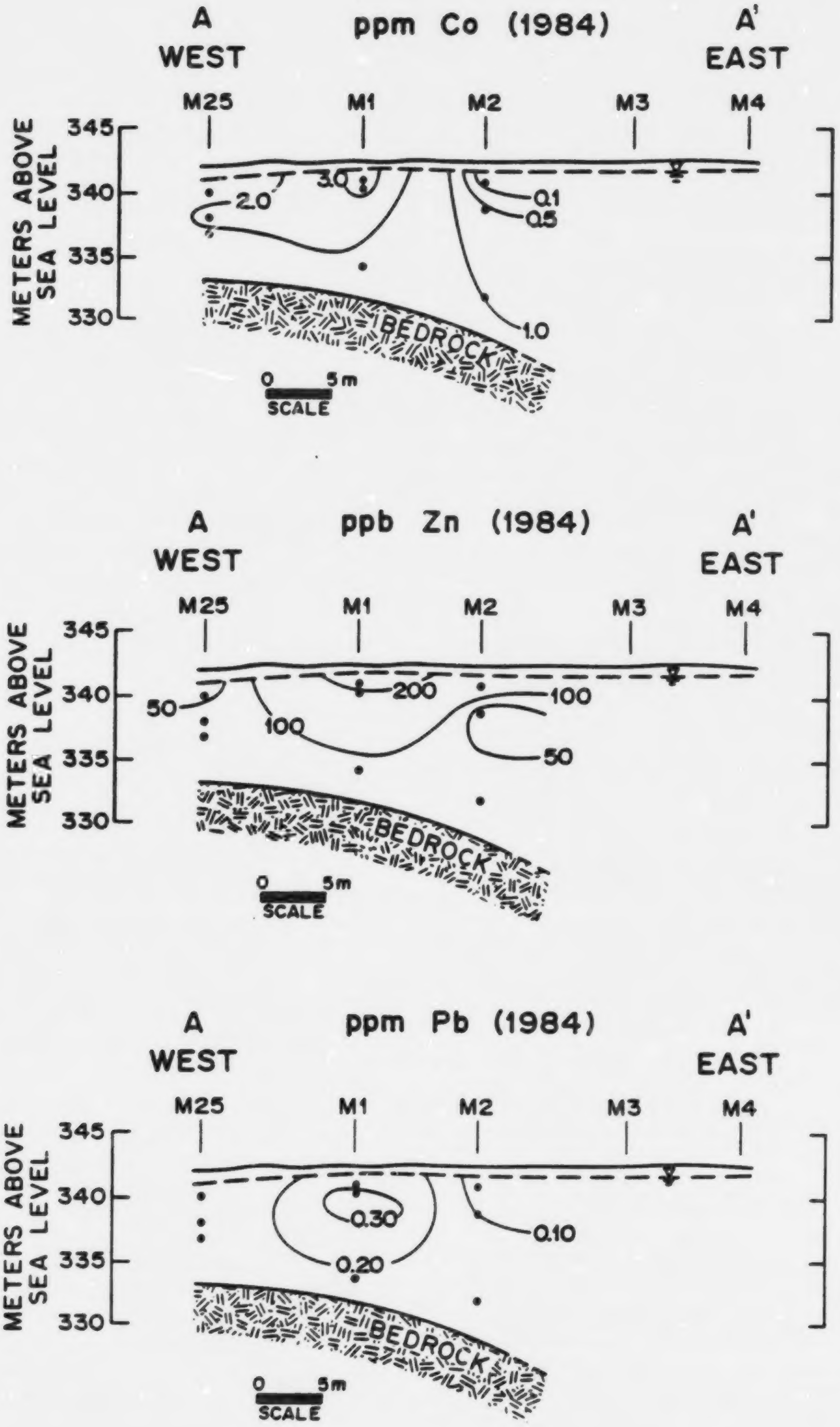


Figure 11. Co, Zn, Pb profiles along Cs. A-A' for 1984.

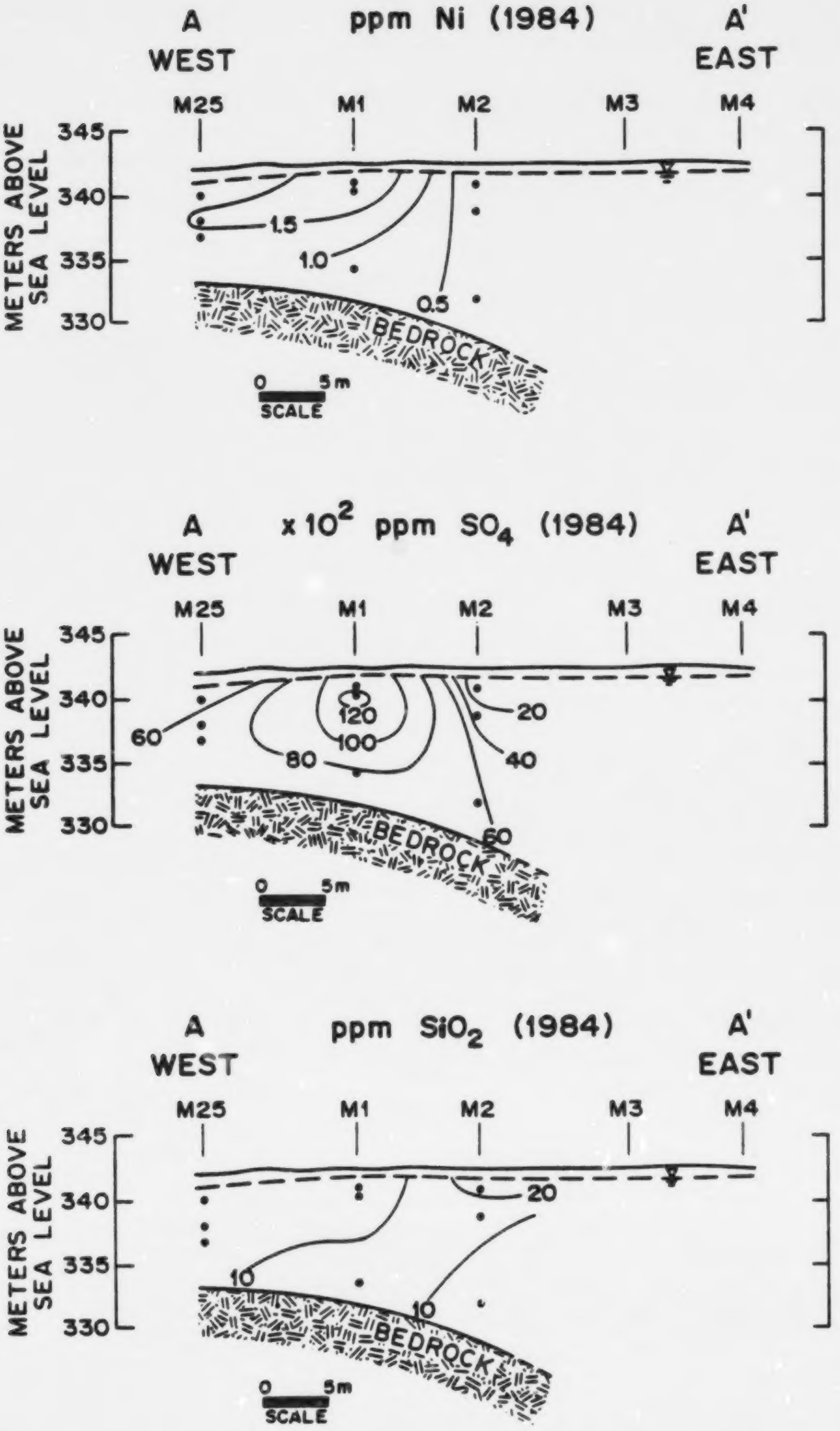


Figure 12. Ni, SO_4, SiO_2 along Cs. A-A' for 1984.

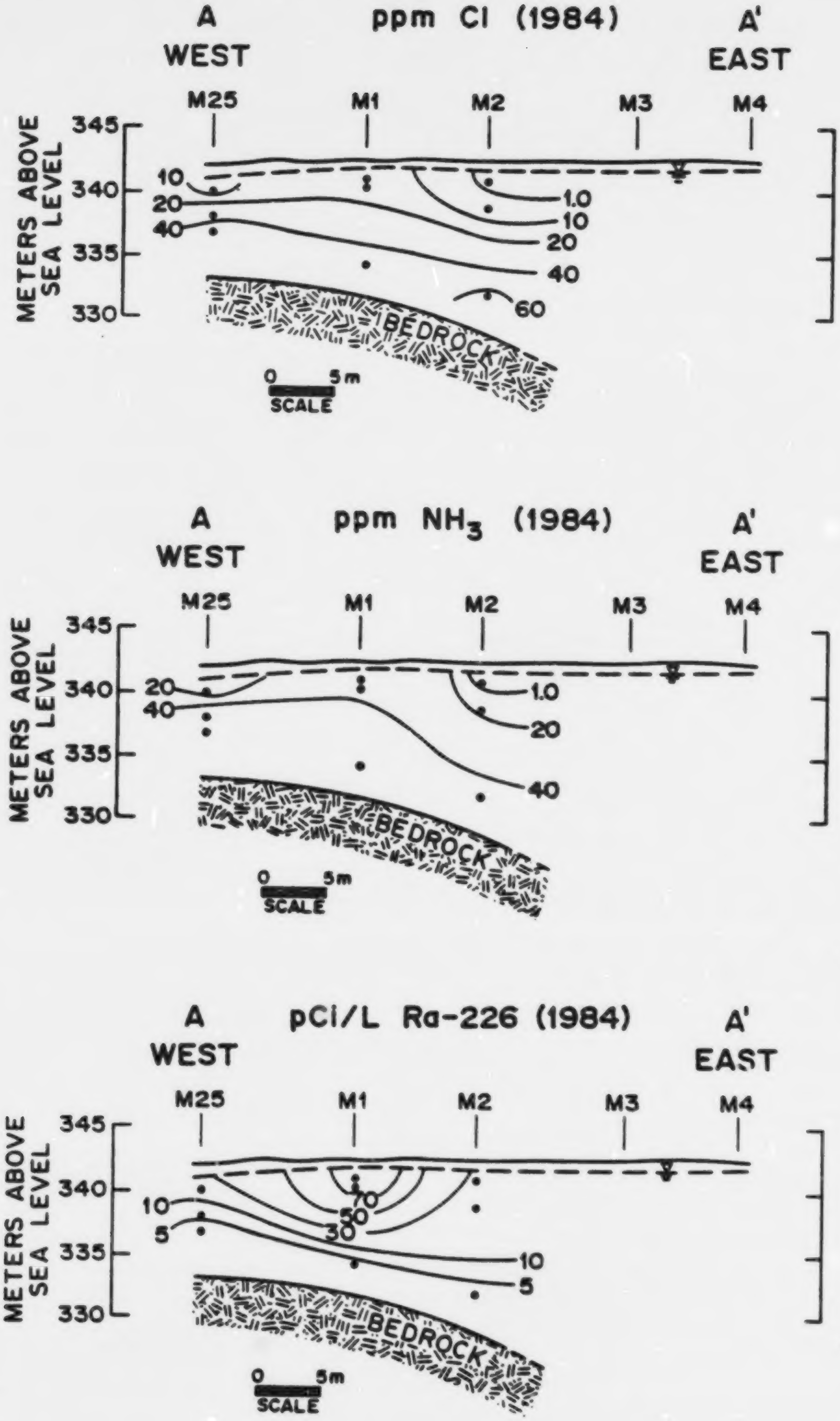


Figure 13. Cl, NH_3, Ra-226 along Cs. A-A' for 1984.

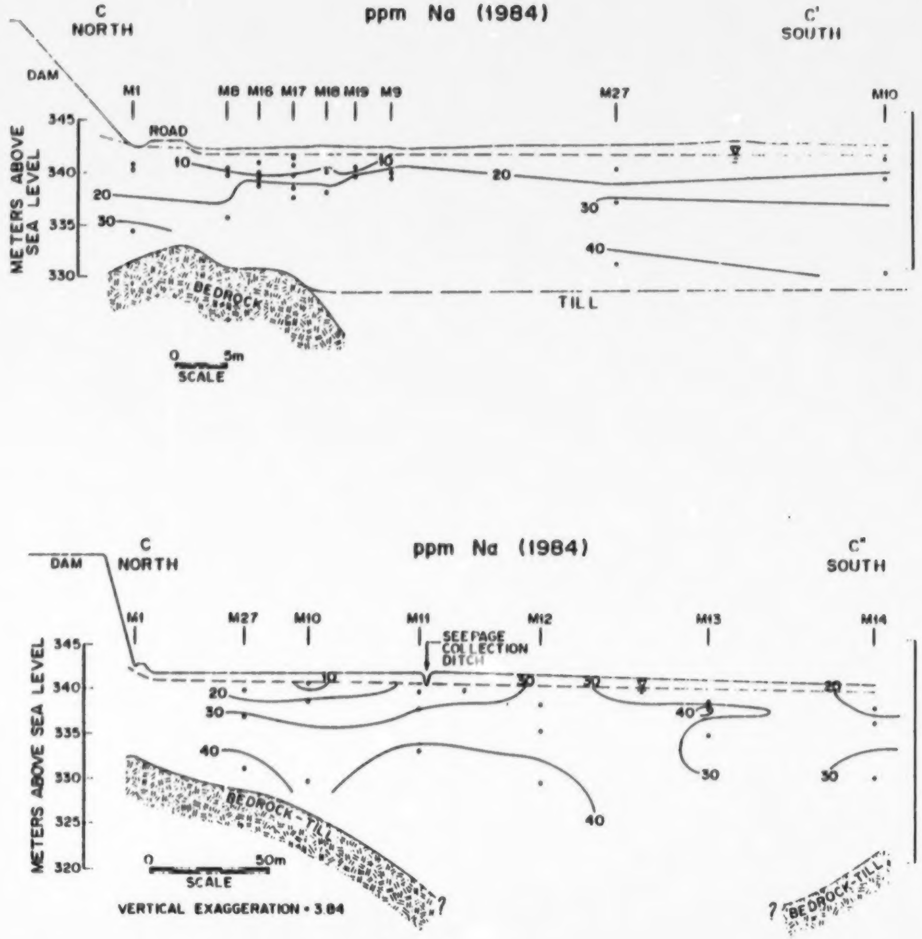


Figure 14. Na profiles along the Centerplane (C-C') and Far Centerplane (C-C") for 1984.

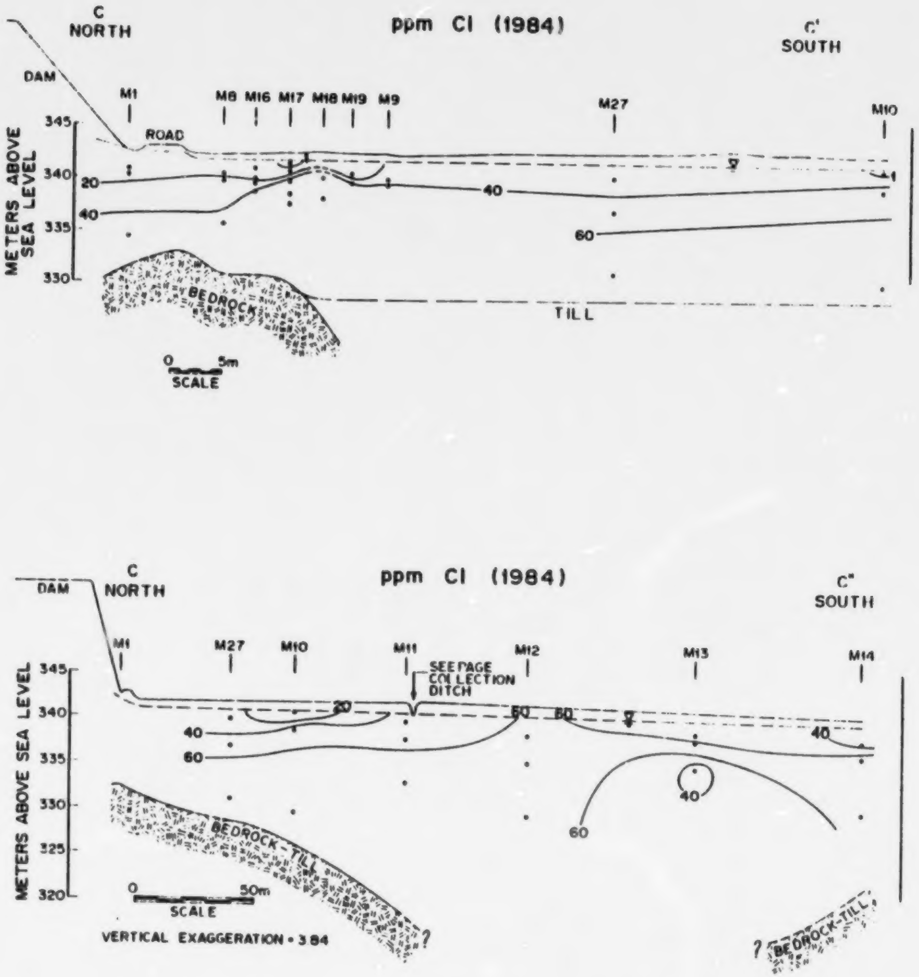


Figure 15. Cl profiles along the Centerplane and Far Centerplane for 1984.

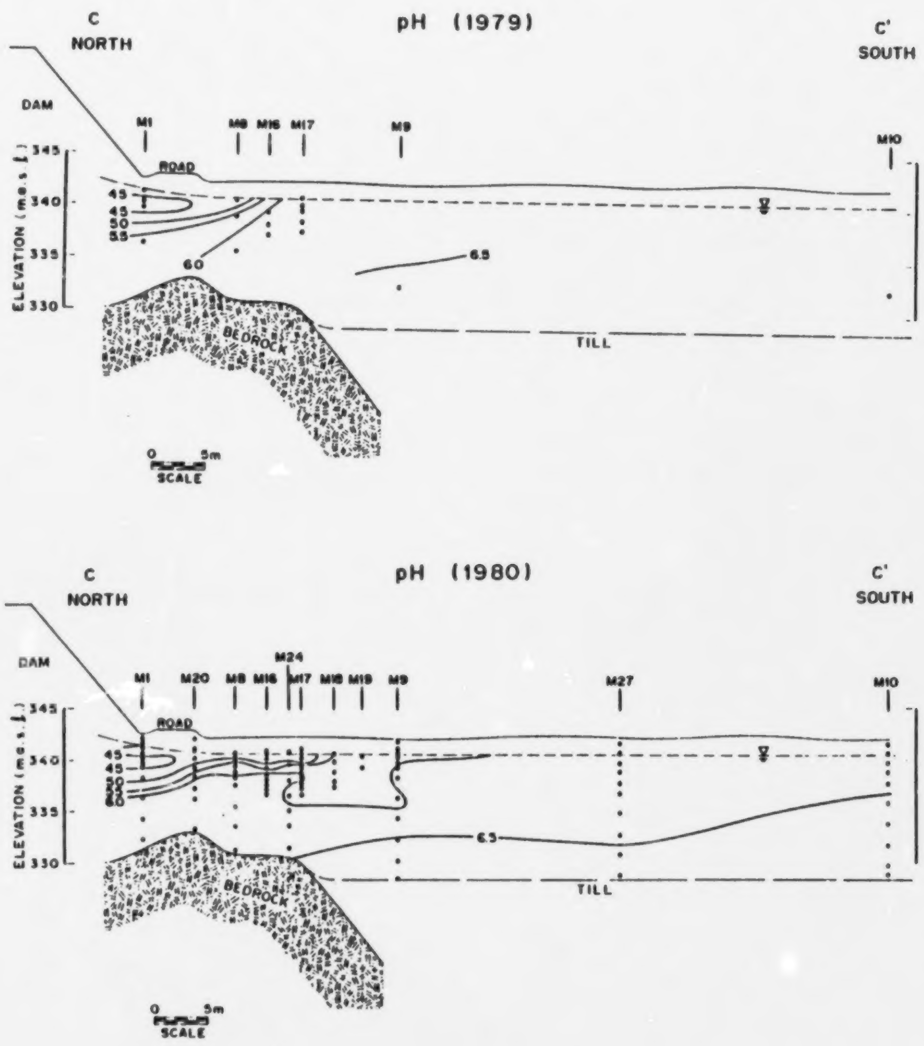


Figure 16. pH profiles along the Centerplane for 1979-1984.

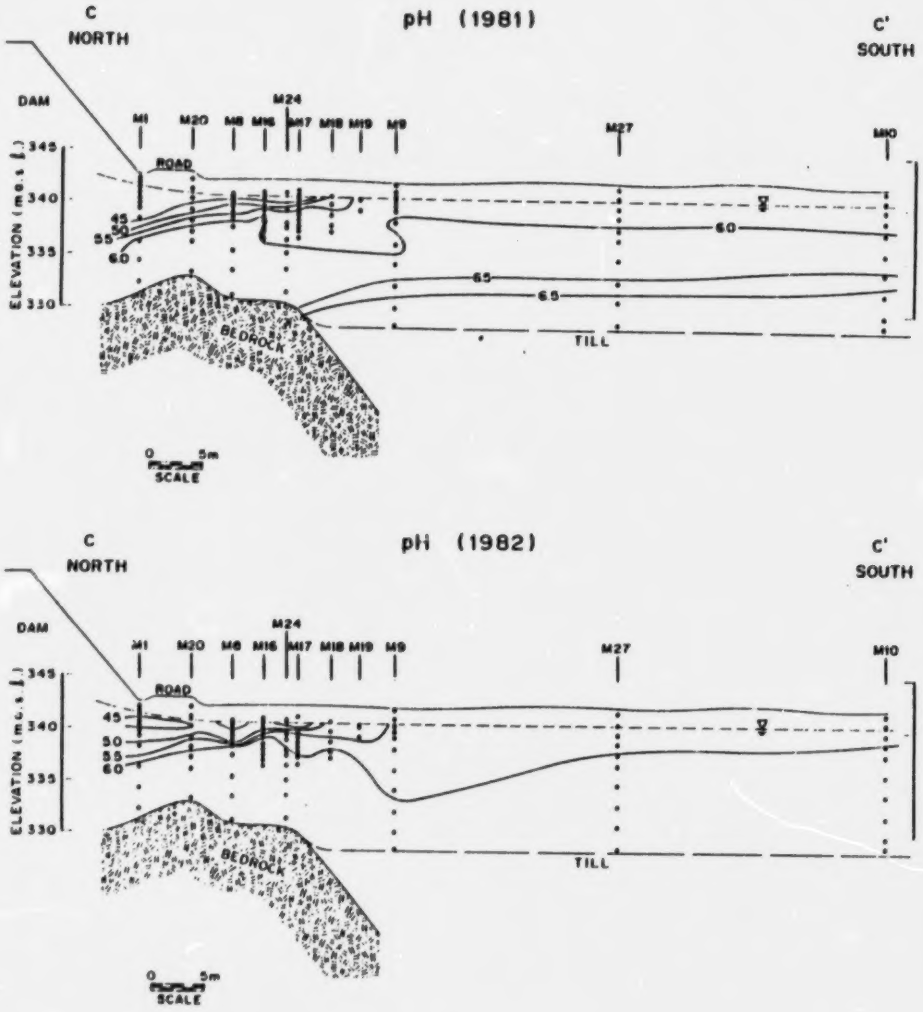


Figure 16. (continued)

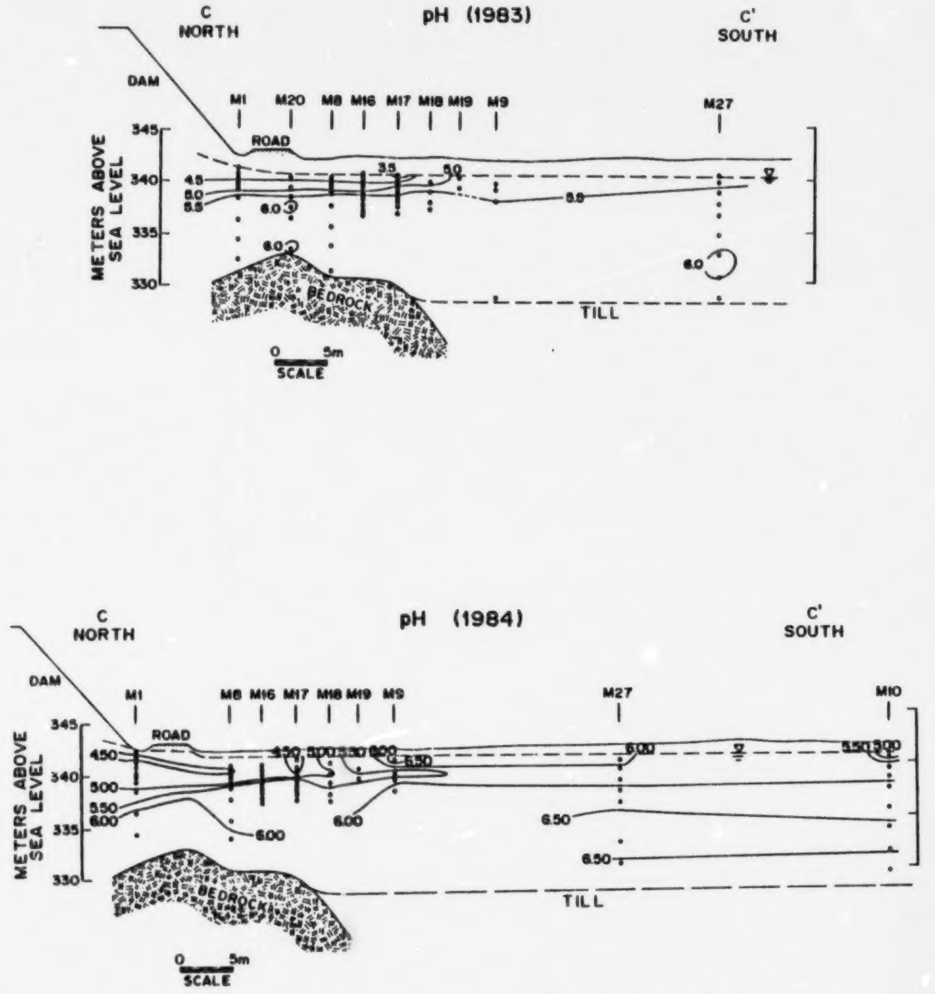


Figure 16. (continued)

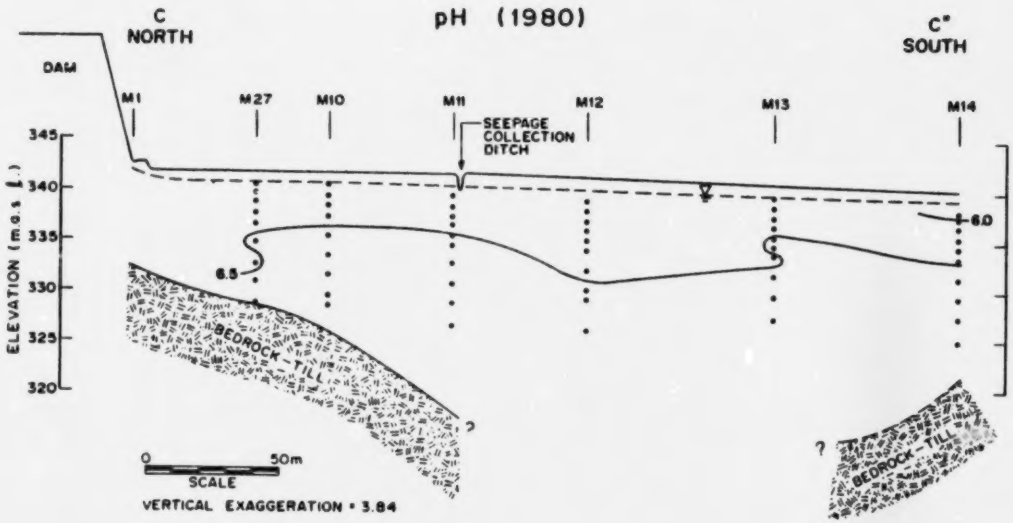
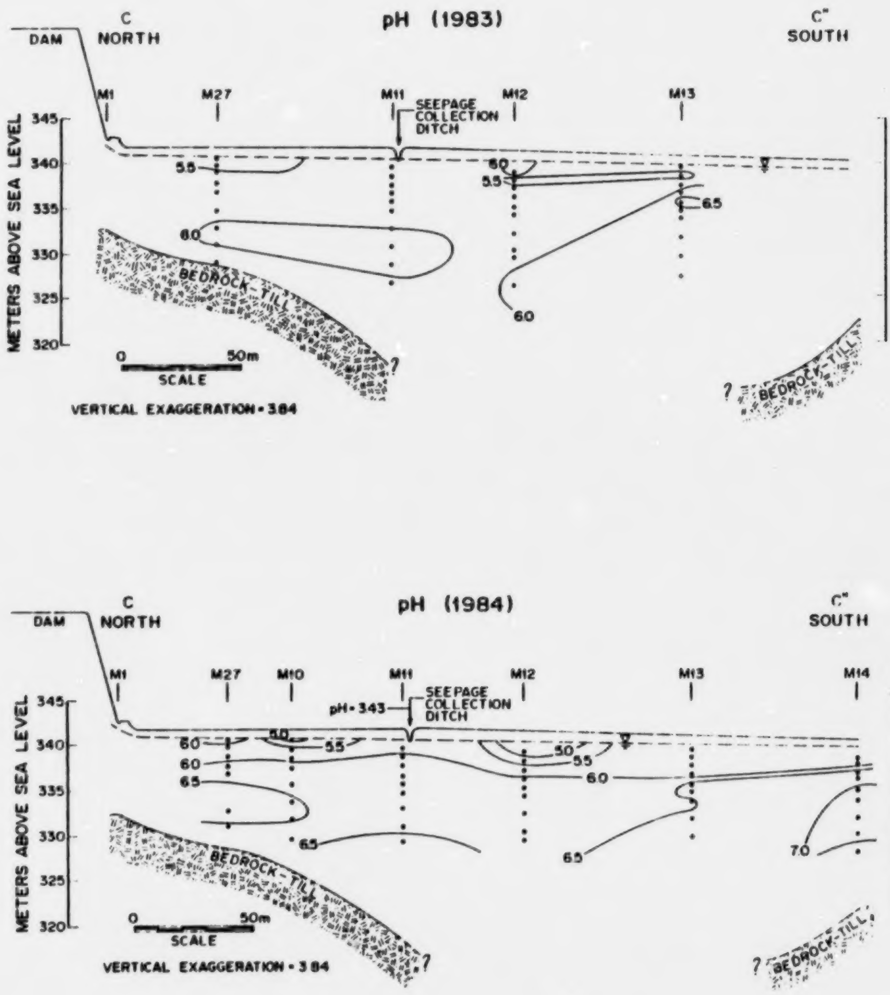


Figure 17. pH profiles along the Far Centerplane for 1980, 1983, and 1984.



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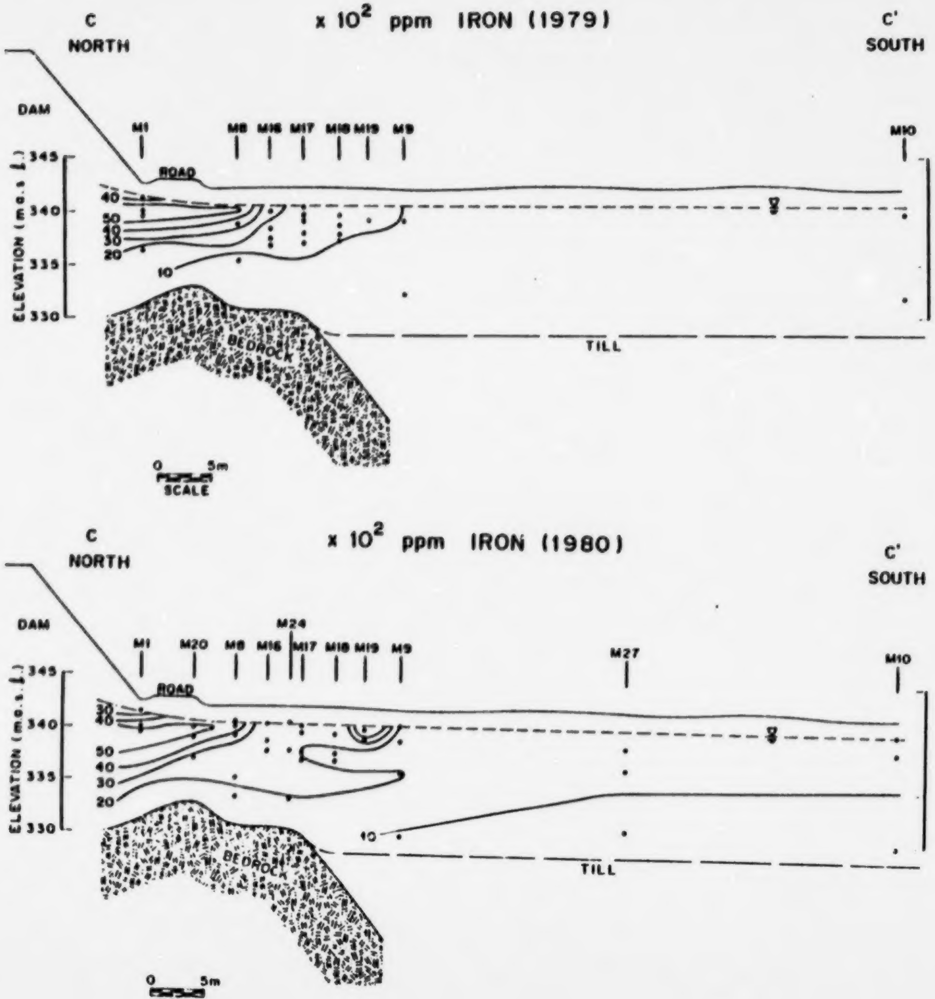


Figure 18. Fe profiles along the Centerplane for 1979-1984.

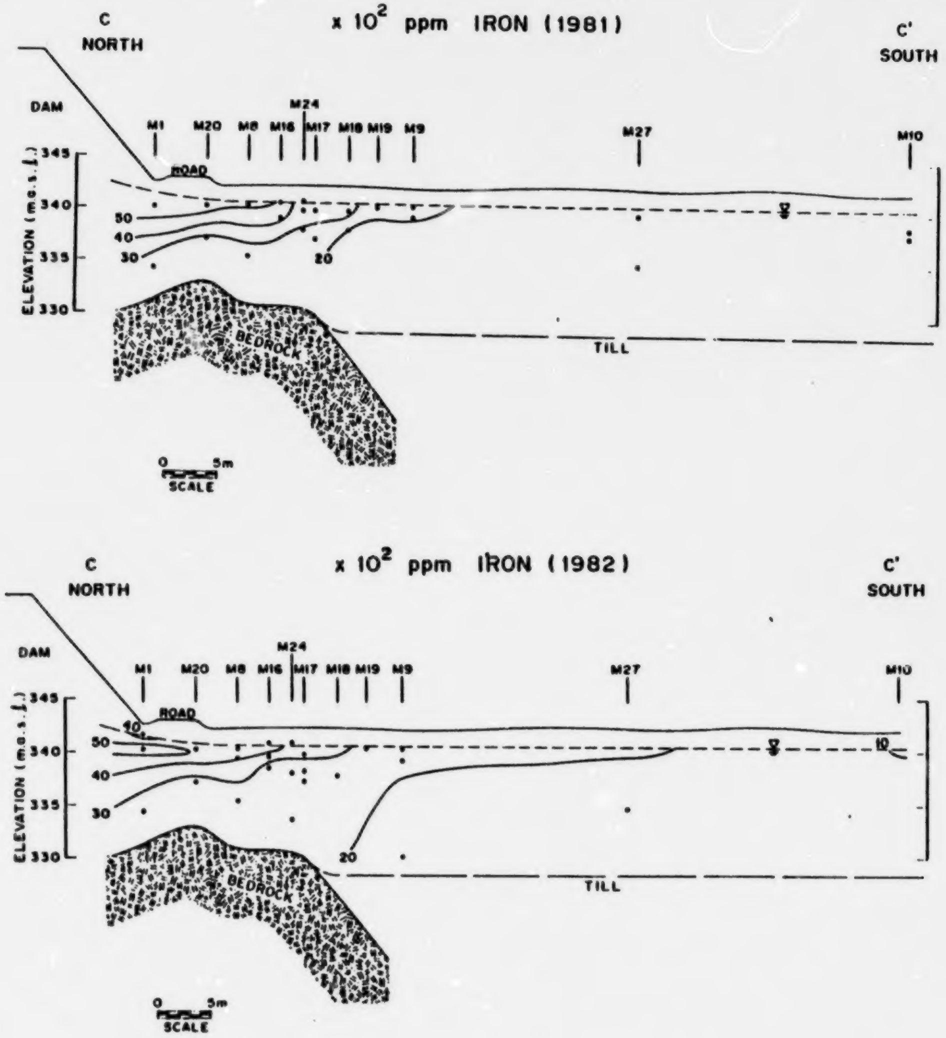
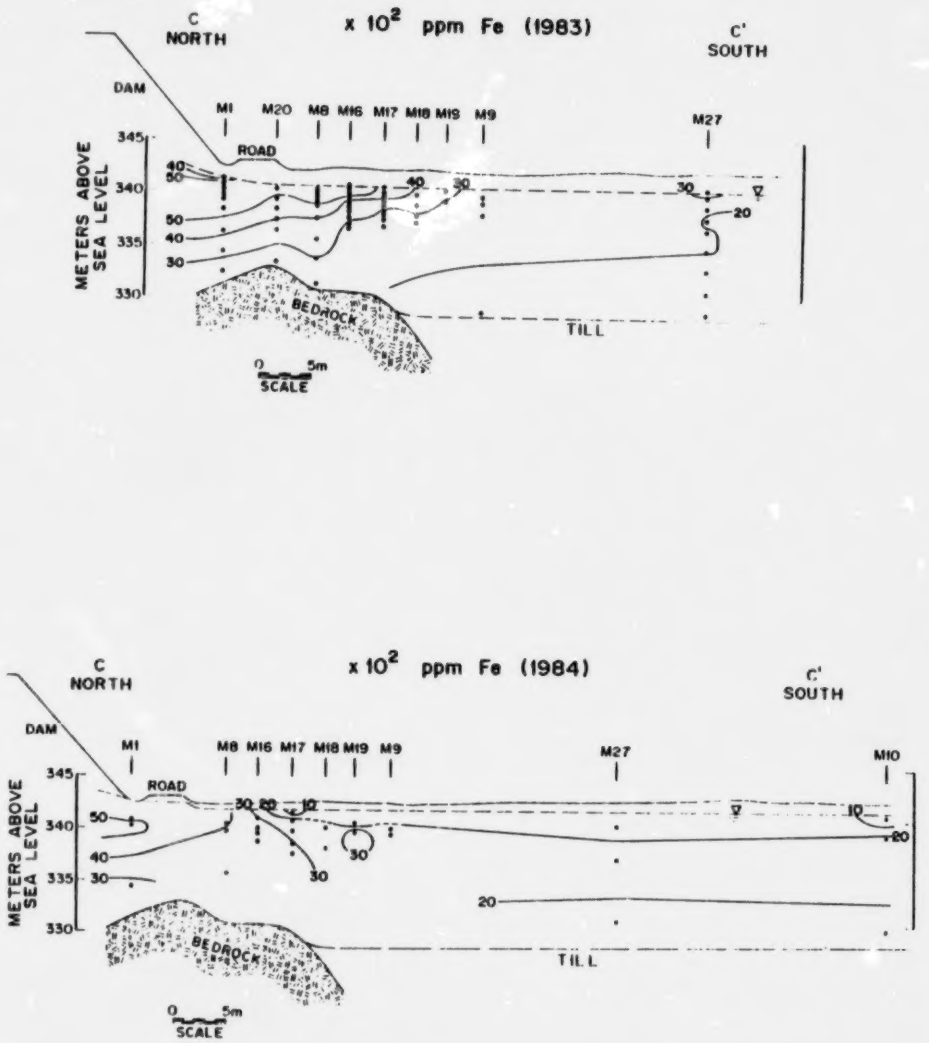


Figure 18. (continued)



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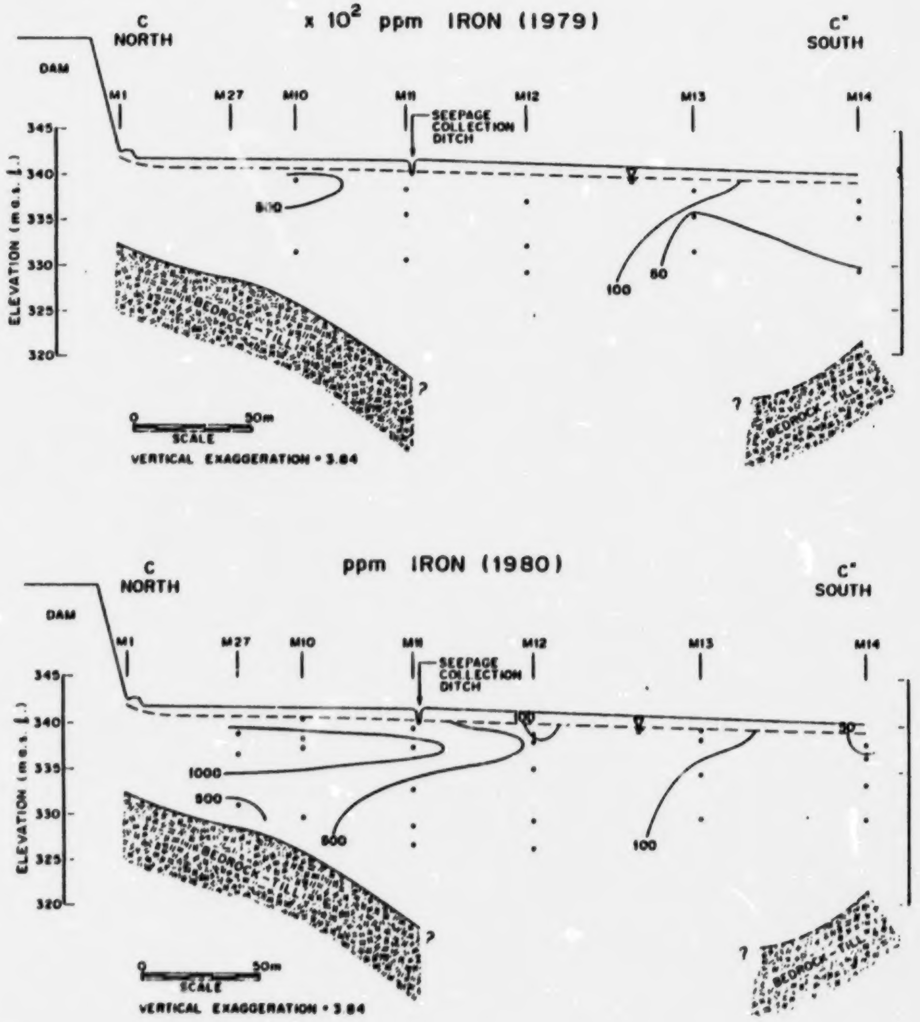
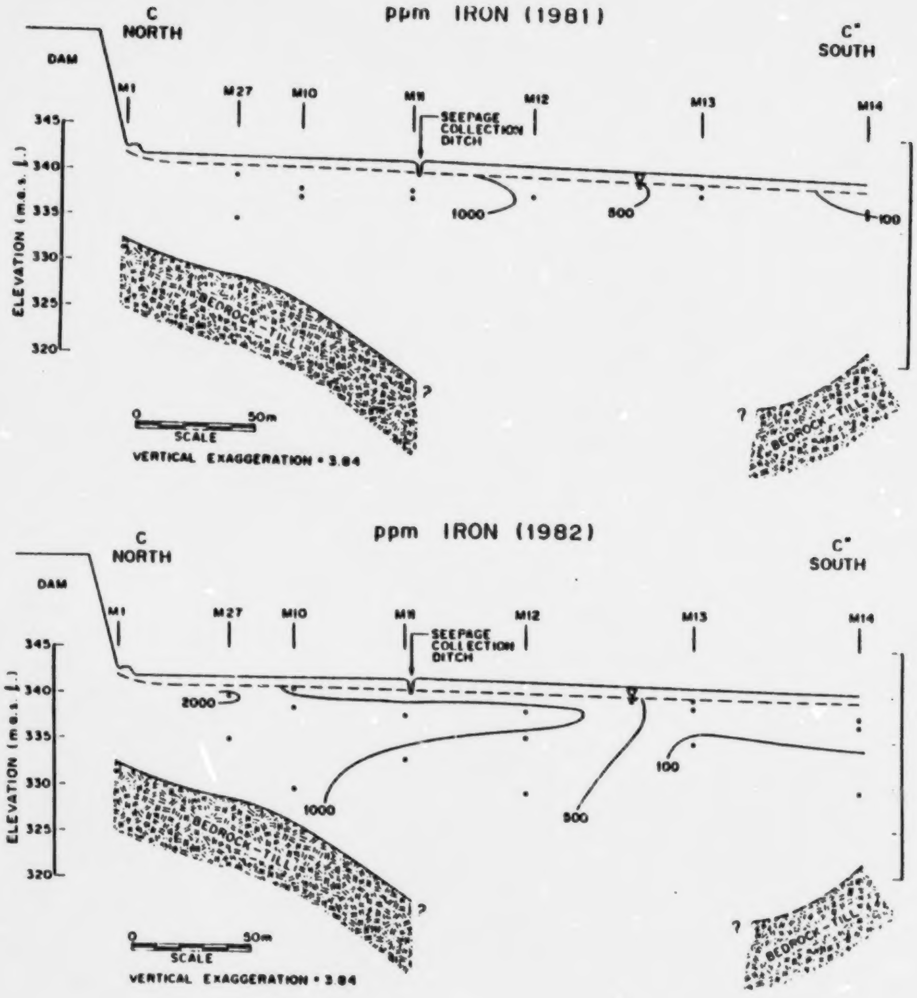


Figure 19. Fe profiles along the Far Centerplane for 1979-1984.



ppm IRON (1981)

ppm IRON (1982)

Figure 19. (continued)

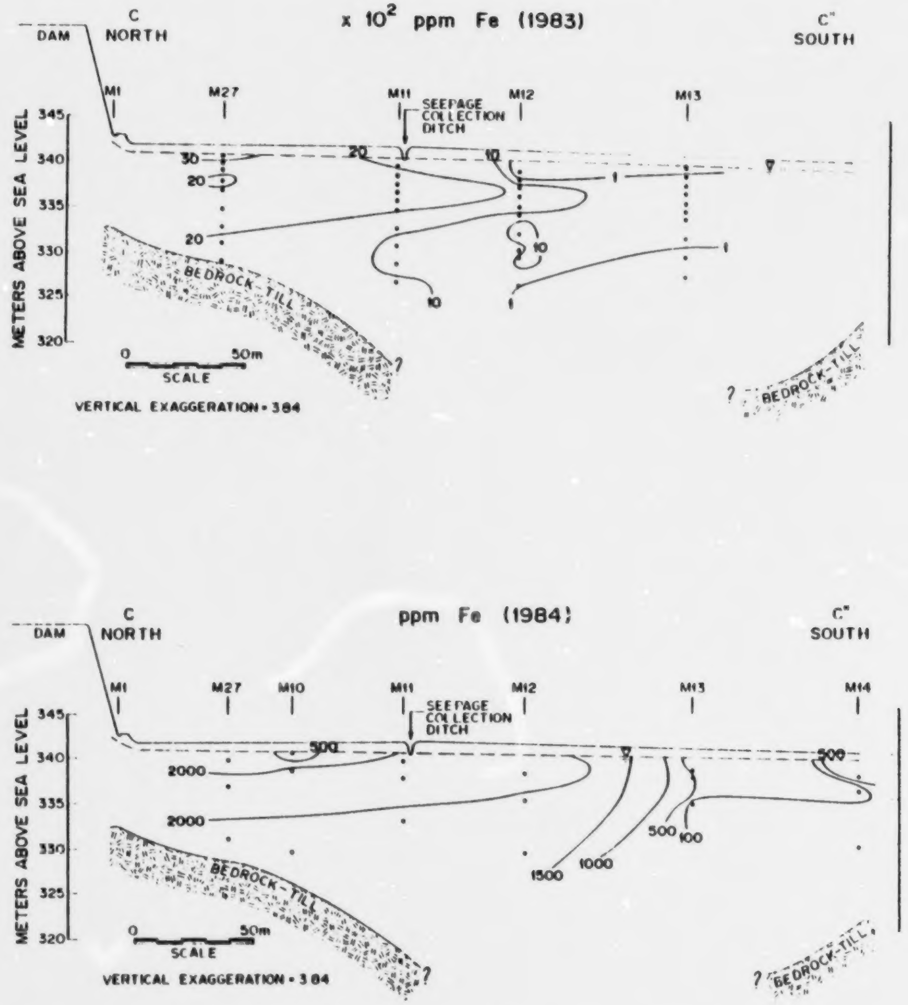


Figure 19. (continued)

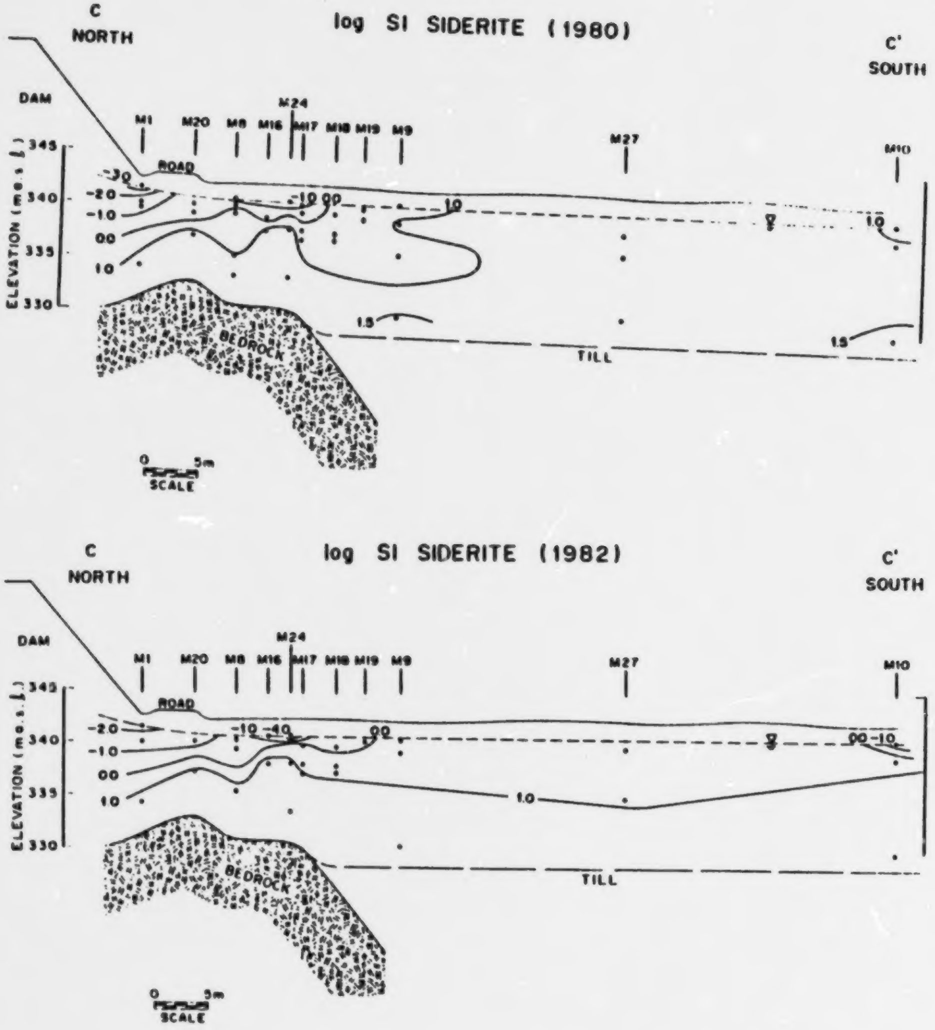


Figure 20. Log SI siderite profiles along the Centerplane for 1980, 1982, and 1984.

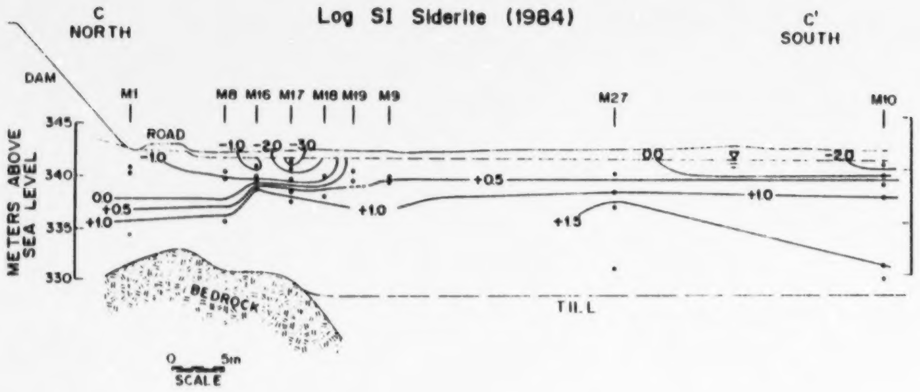


Figure 20. (continued)

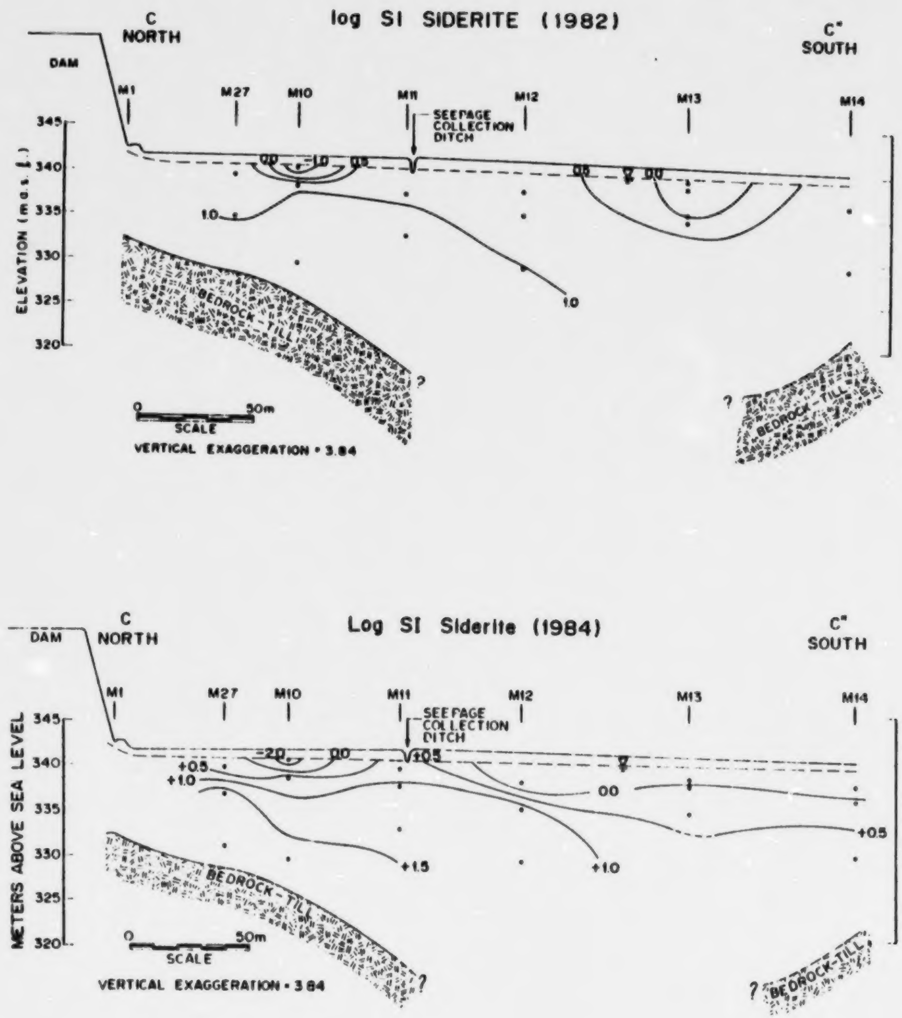


Figure 21. Log SI siderite profiles along the Far Centerplane for 1982 and 1984.

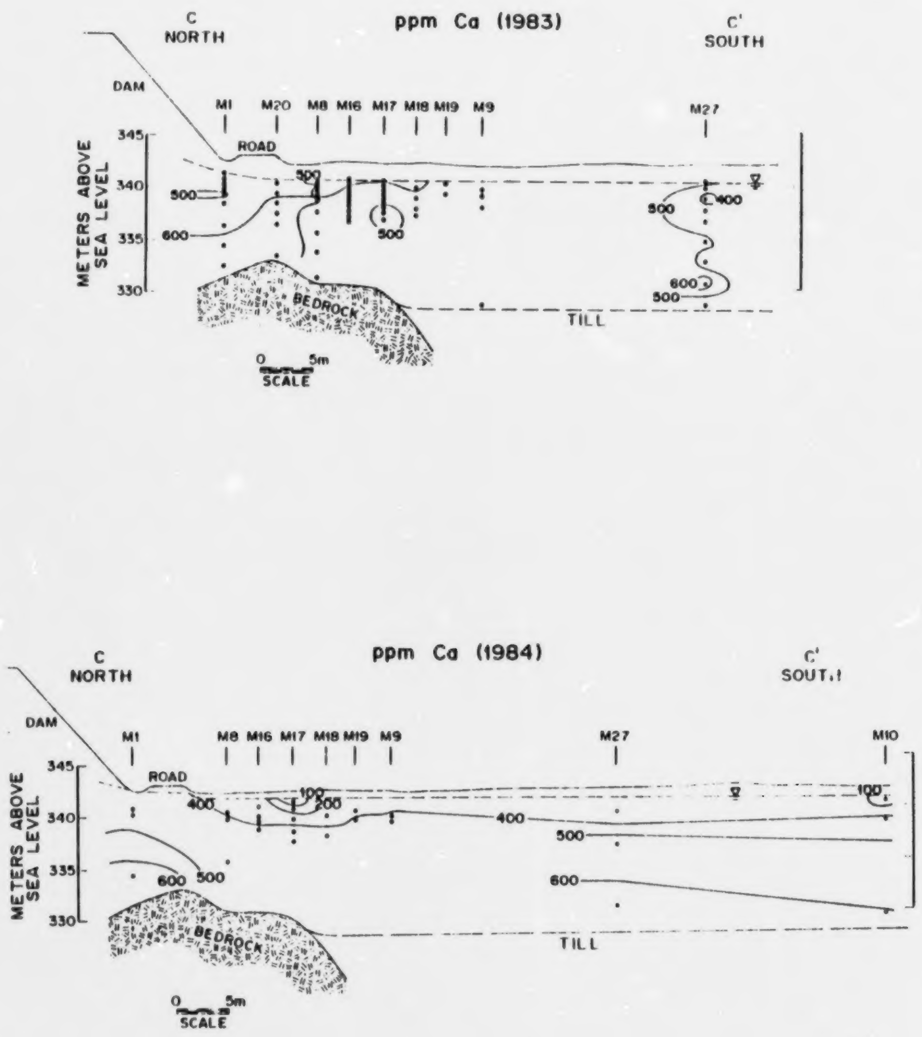


Figure 22. Ca profiles along the Centerplane for 1983 and 1984.

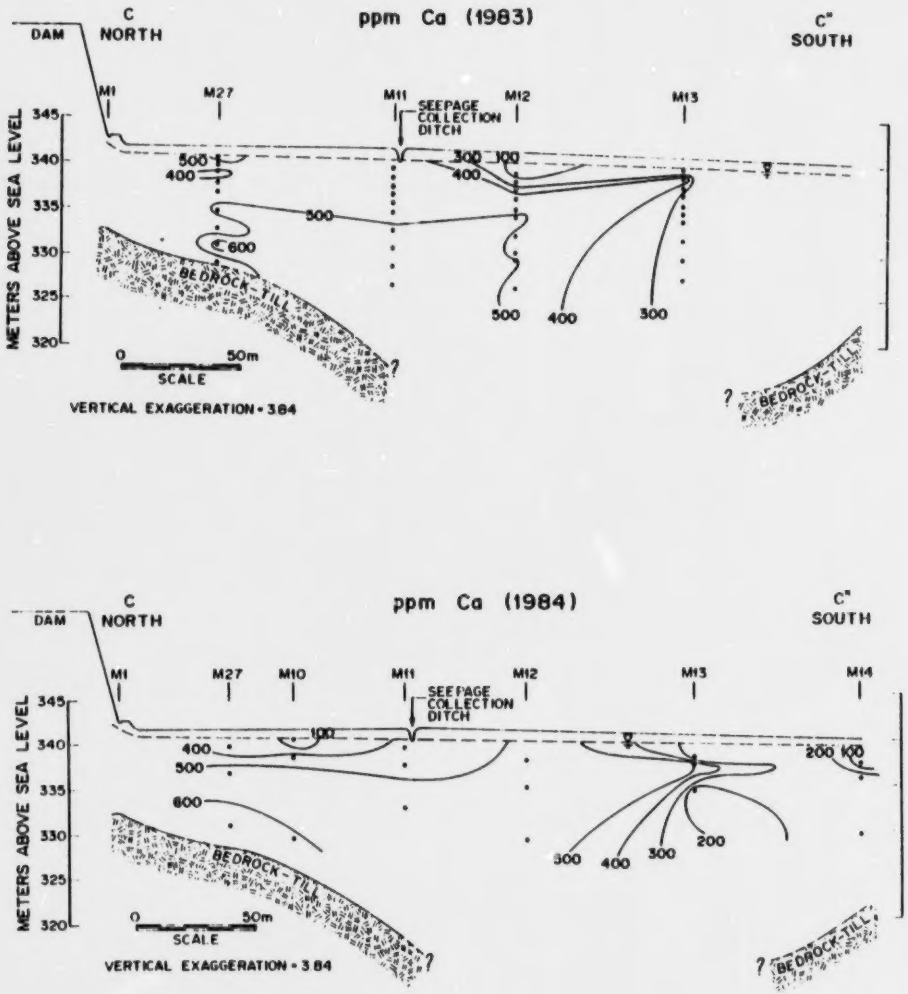


Figure 23. Ca profiles along the Far Centerplane for 1983 and 1984.

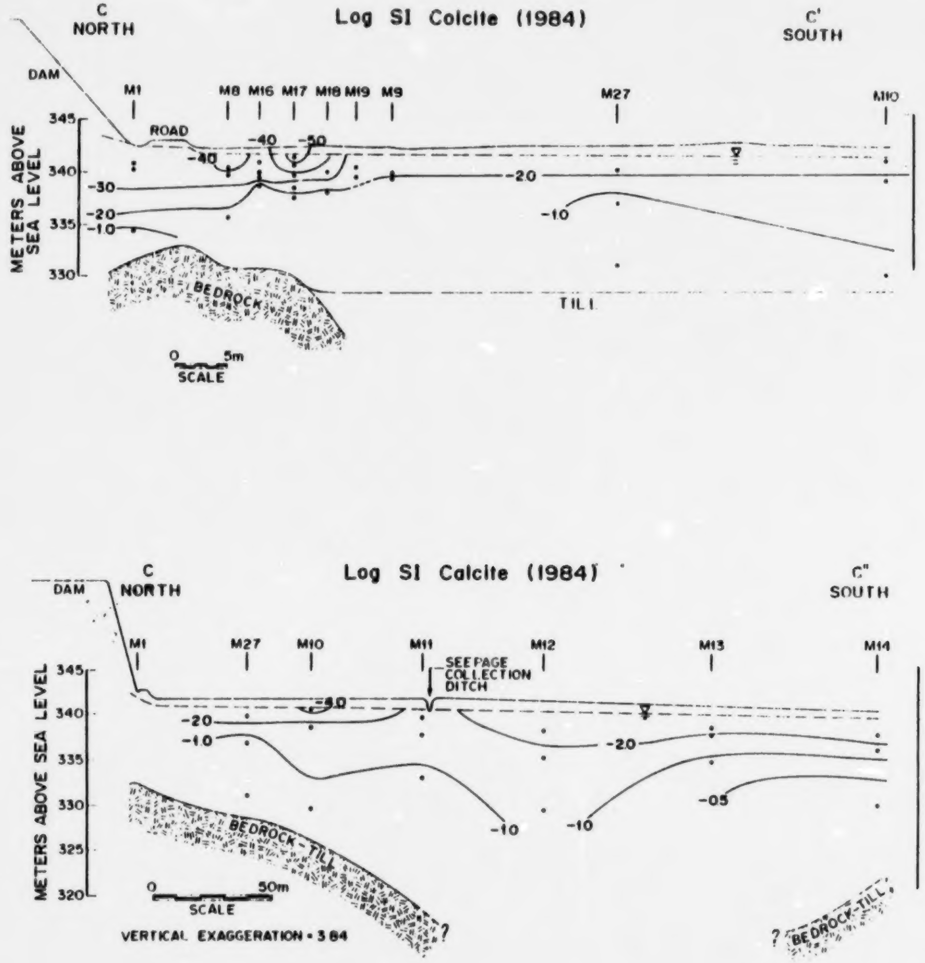


Figure 24. Log SI calcite profiles along the Centerplane and Far Centerplane for 1984.

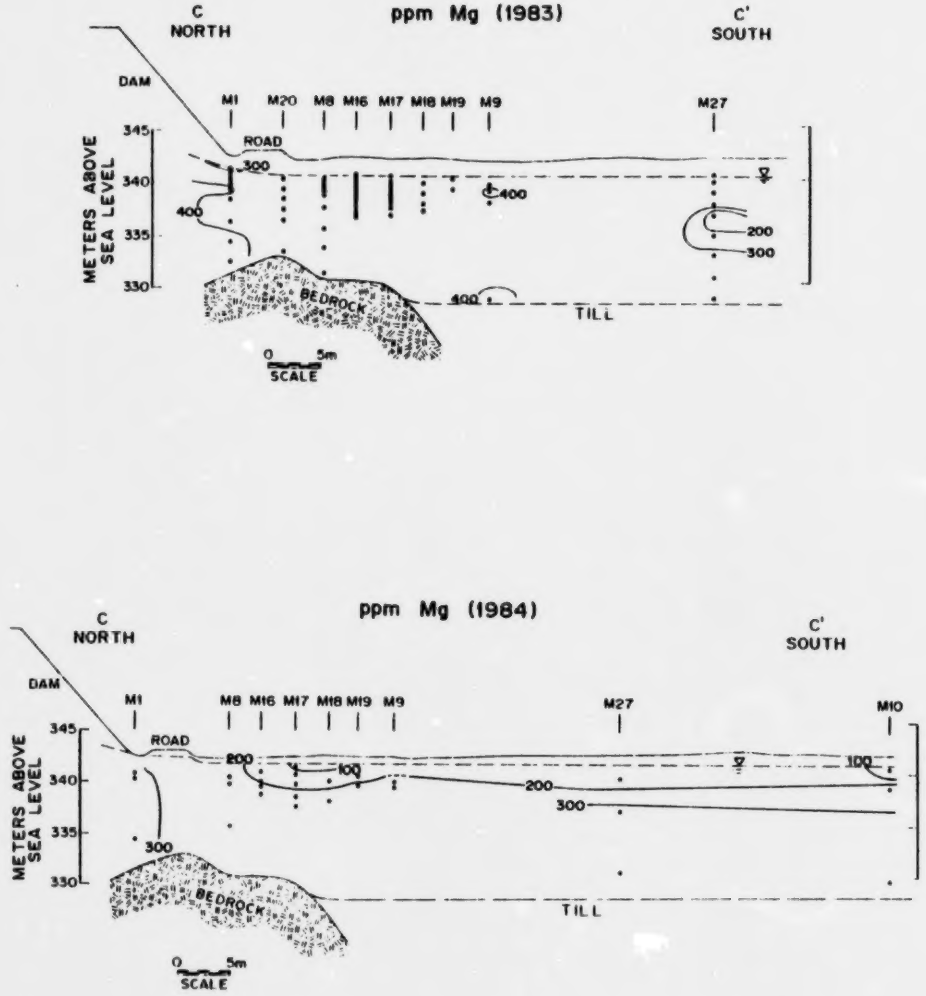


Figure 25. Mg profiles along the Centerplane for 1983 and 1984.

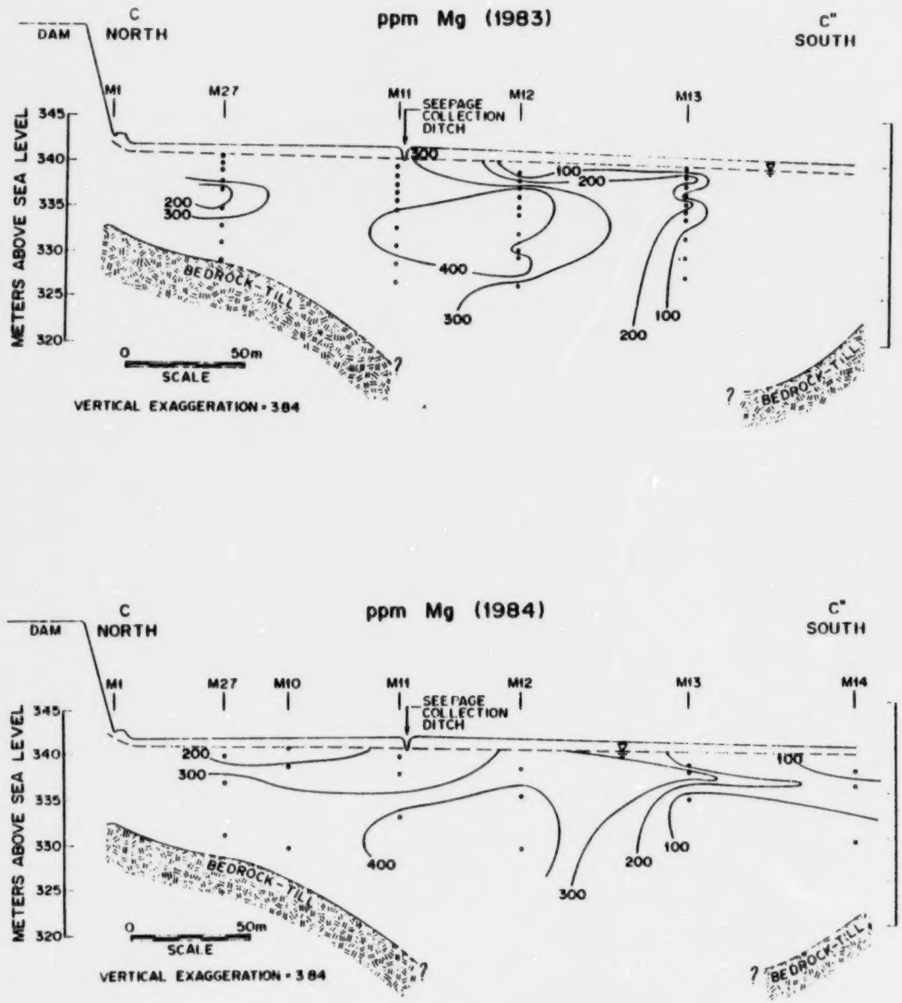


Figure 26. Mg profiles along the Far Centerplane for 1983 and 1984.

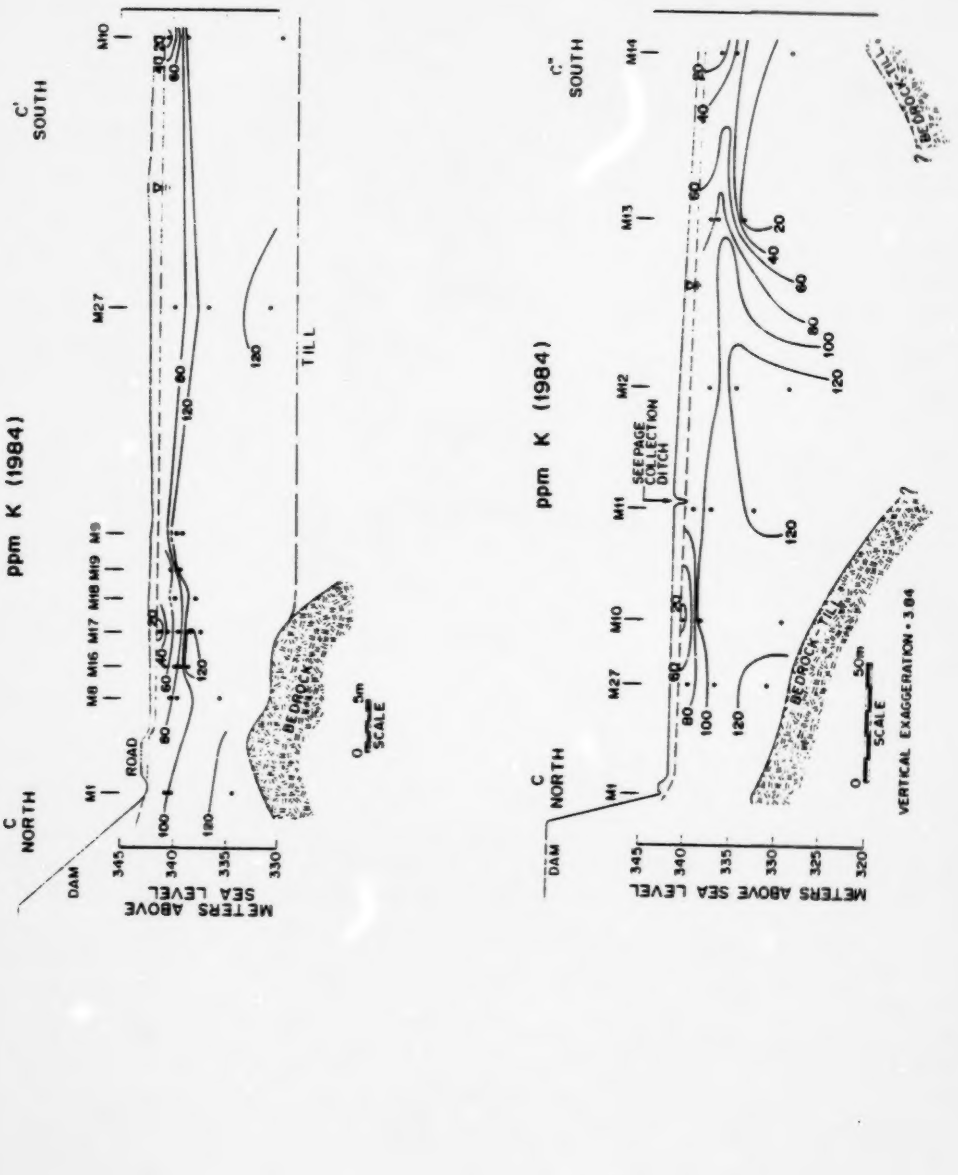


Figure 27. K profiles along the Centerplane and Far Centerplane for 1984.

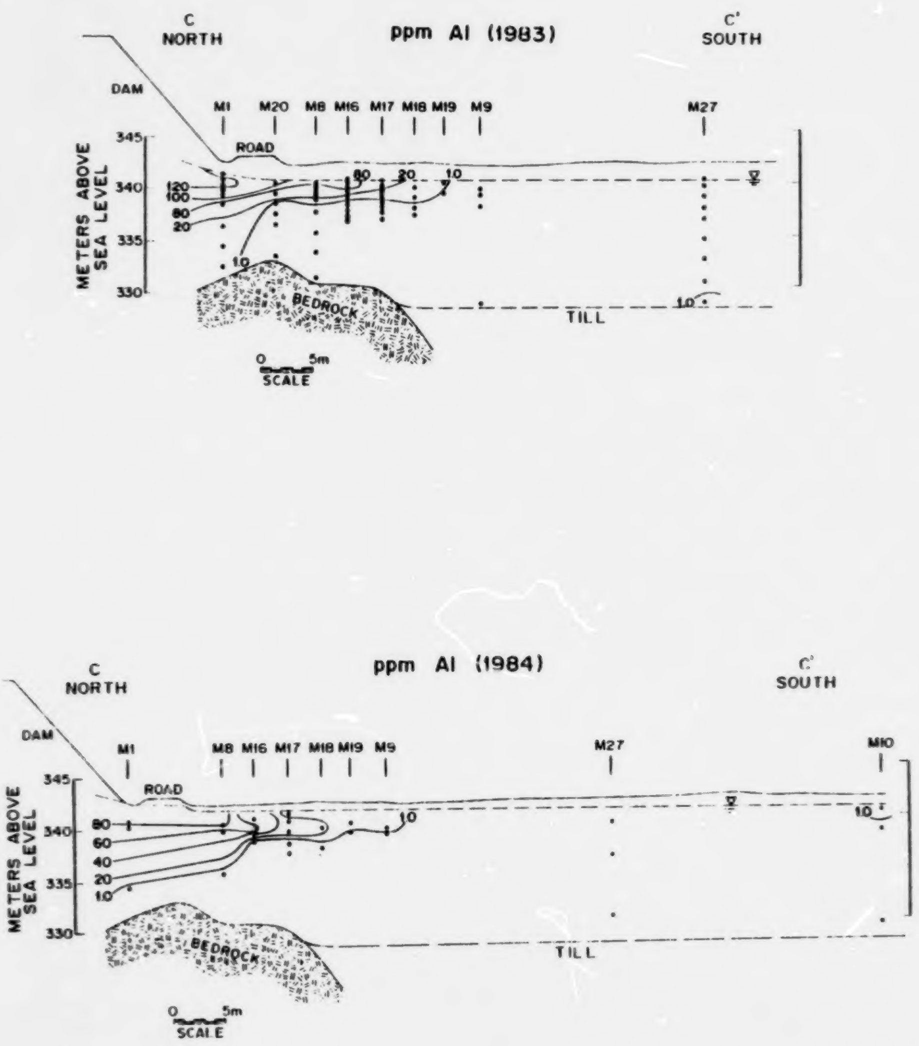


Figure 28. Al profiles along the Centerplane for 1983 and 1984.

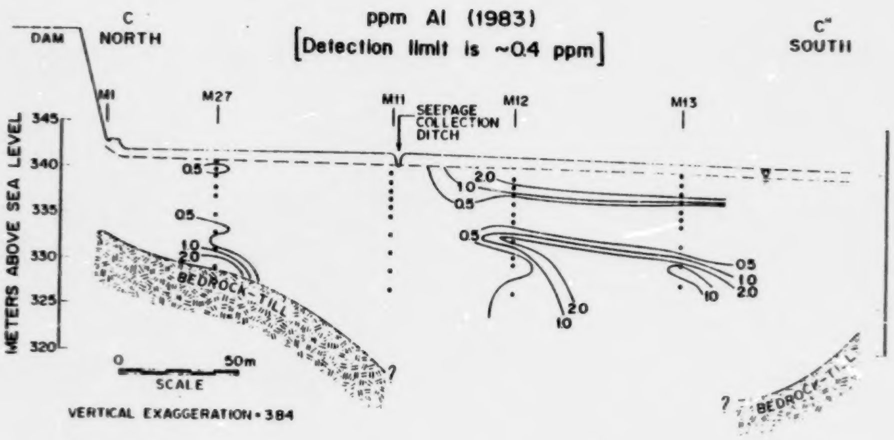


Figure 29. Al profile along the Far Centerplane for 1983.

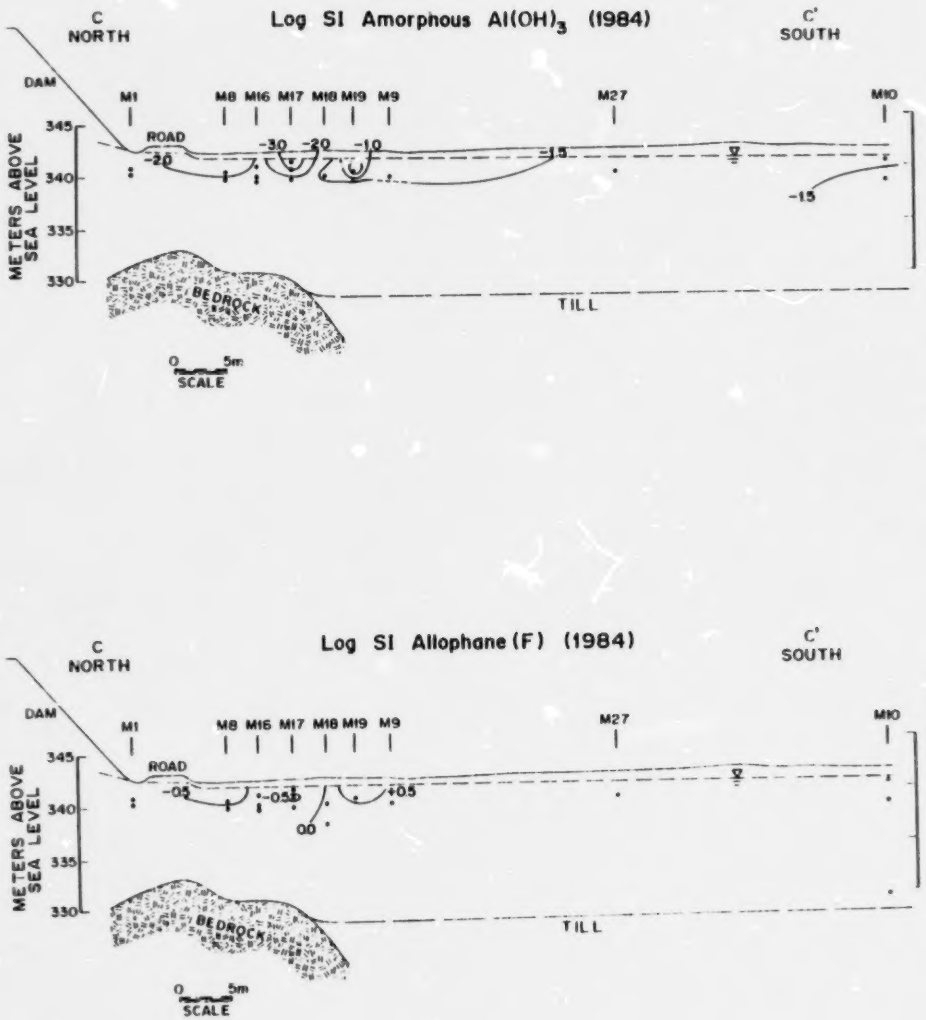


Figure 30. Log SI amorphous Al$(OH)_3$ and log SI allophane profiles along the Centerplane for 1984.

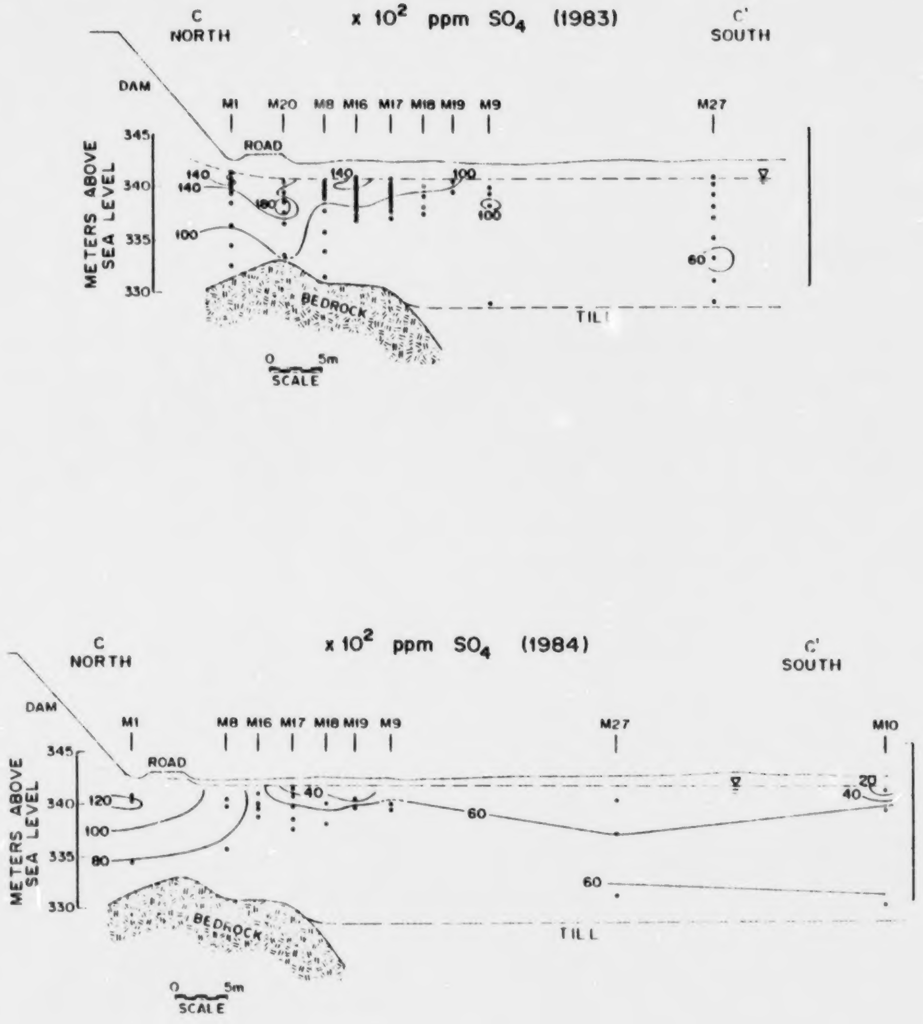


Figure 31. SO_4 profiles along the Centerplane for 1983 and 1984.

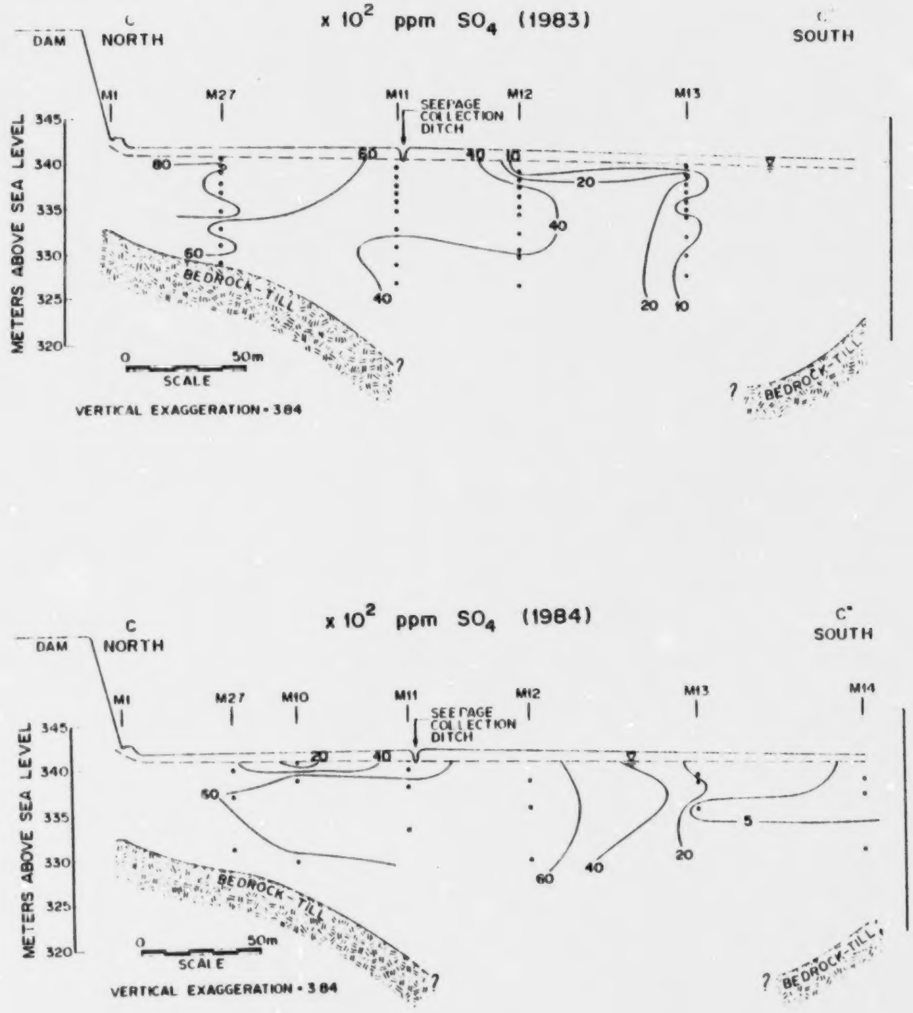


Figure 32. SO_4 profiles along the Far Centerplane for 1983 and 1984.

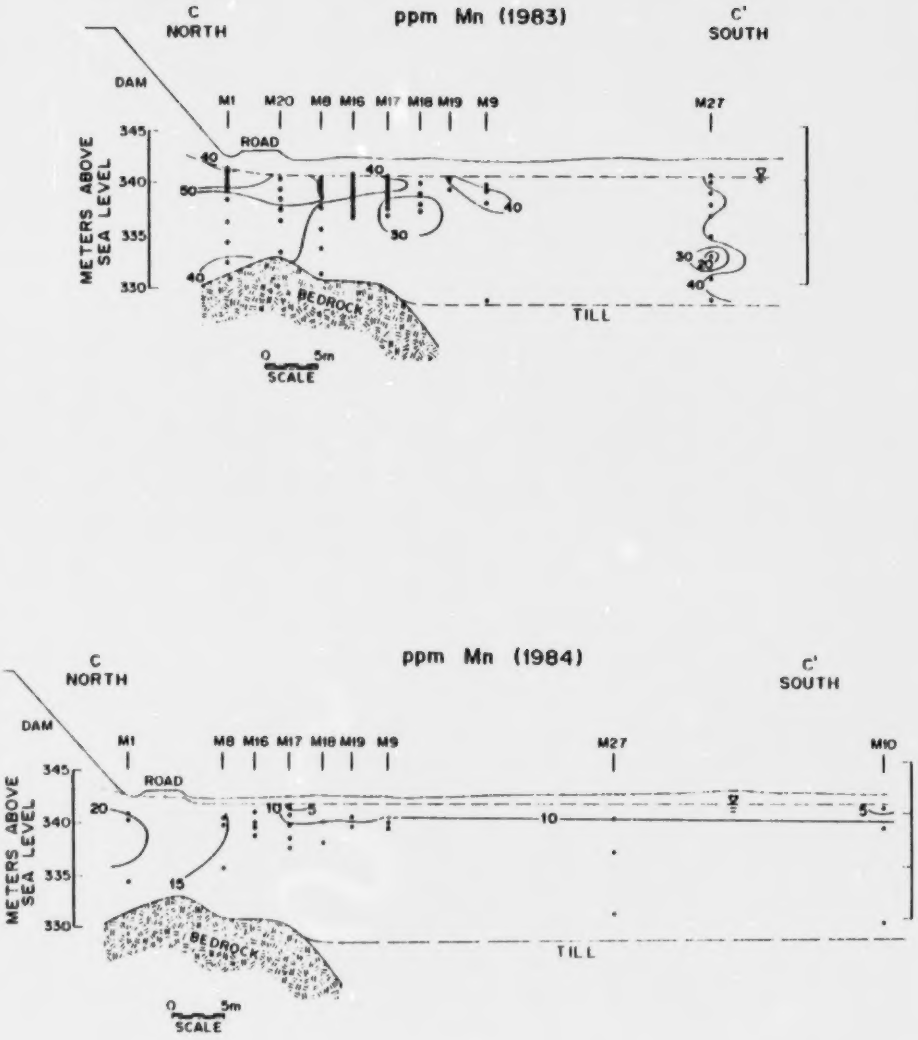


Figure 33. Mn profiles along the Centerplane for 1983 and 1984.

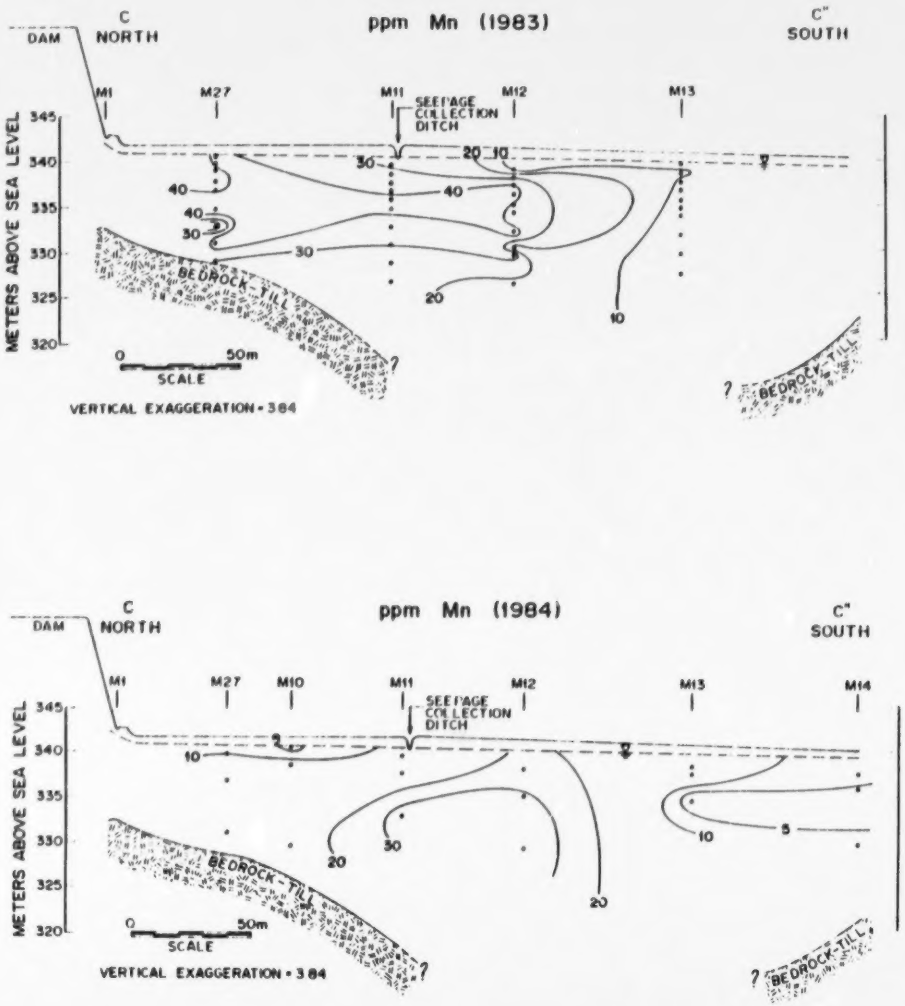


Figure 34. Mn profiles along the Far Centerplane for 1983 and 1984.

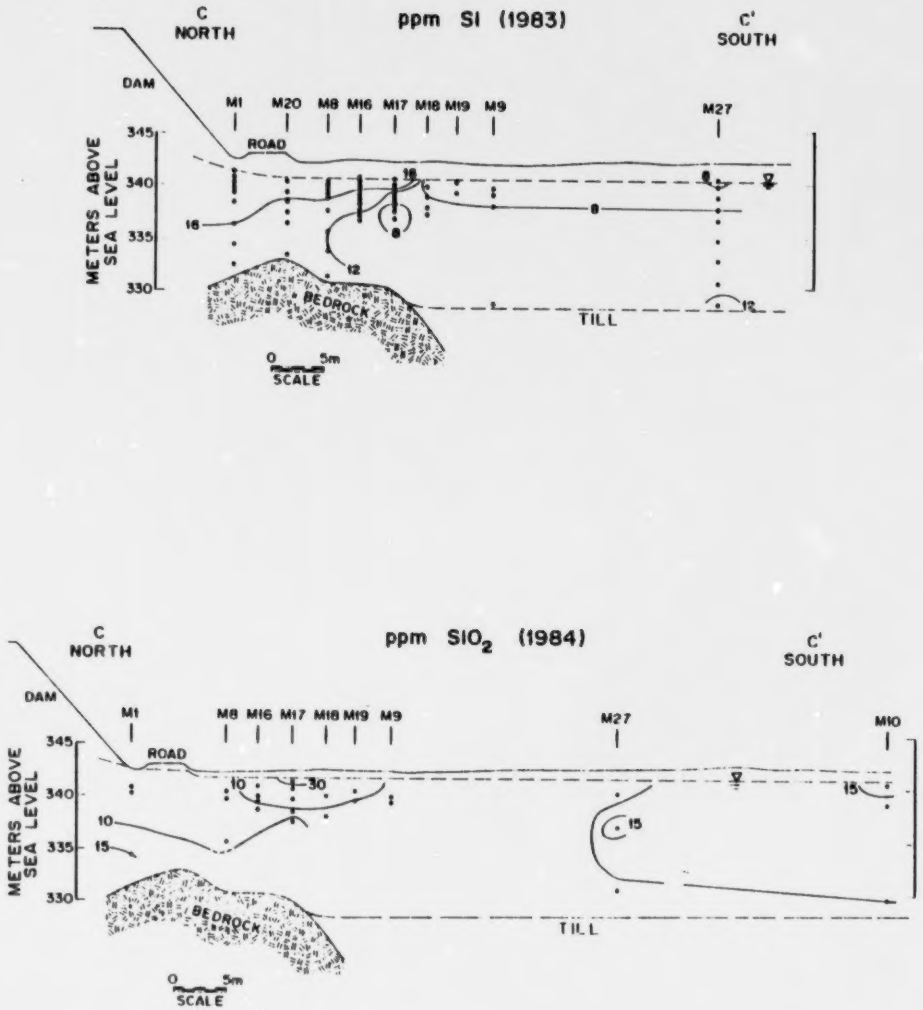


Figure 35. Si and SiO_2 profiles along the Centerplane for 1983 and 1984.

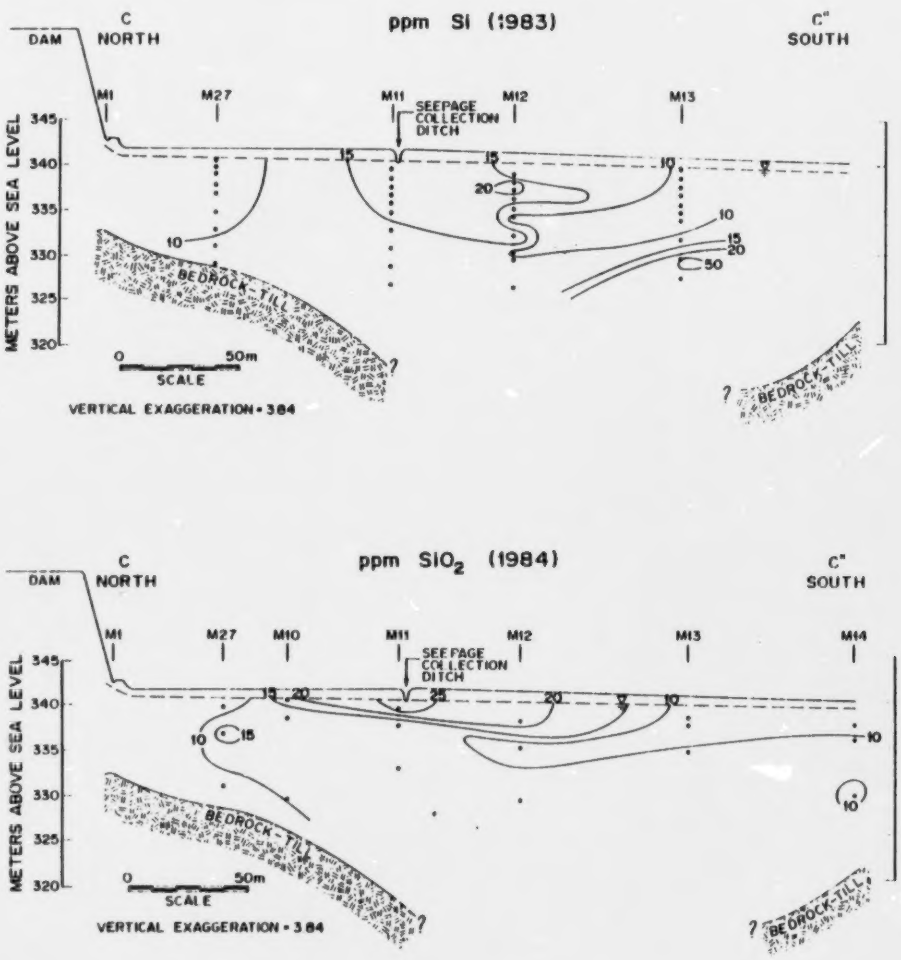


Figure 36. Si and SiO_2 profiles along the Far Centerplane for 1983 and 1984.

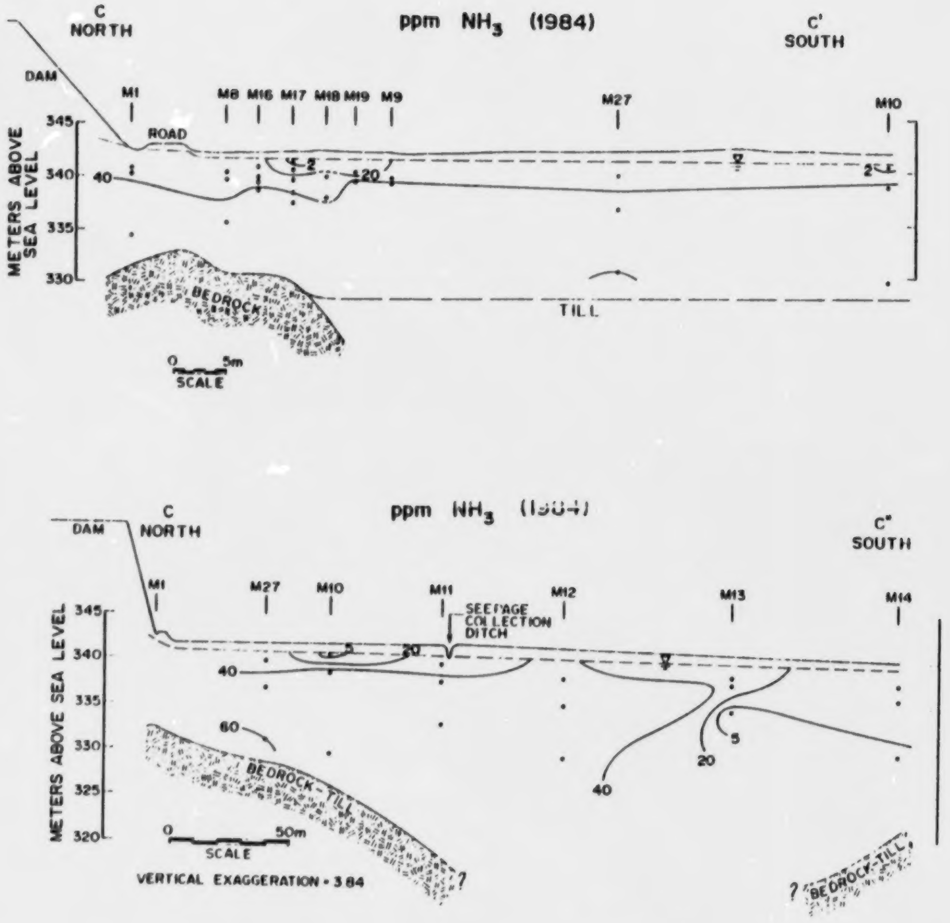


Figure 37. NH_3 profiles along the Centerplane and Far Centerplane for 1984.

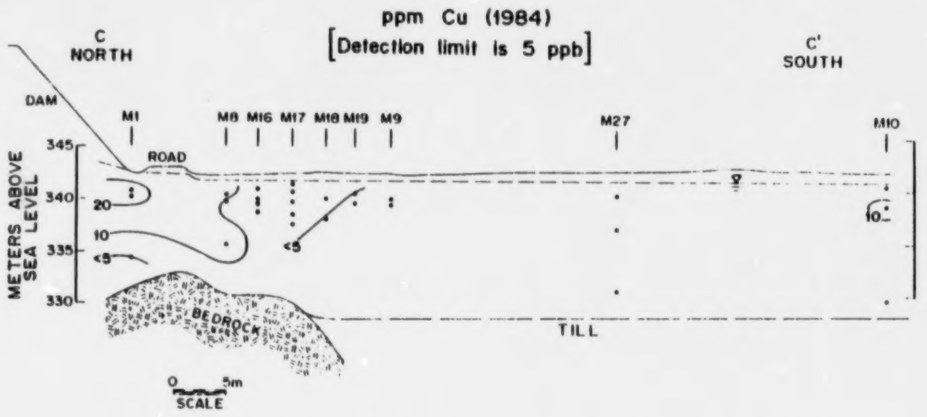


Figure 38. Cu profile along the Centerplane in 1984.

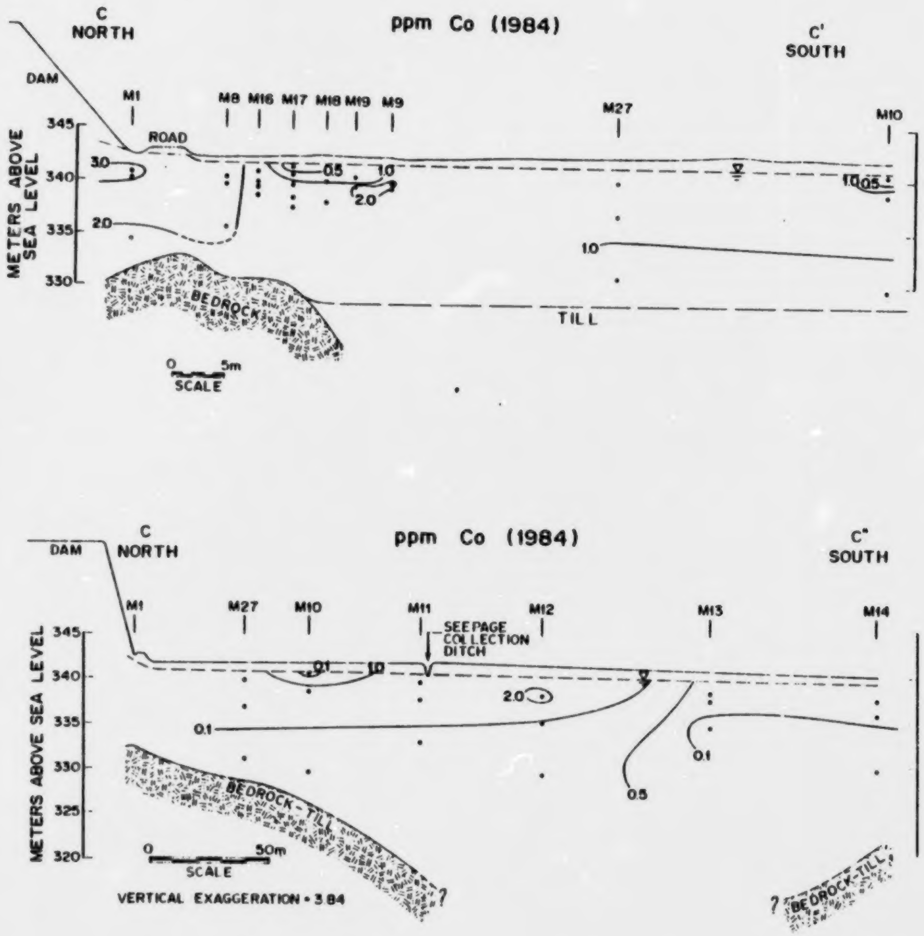


Figure 39. Co profiles along the Centerplane and Far Centerplane for 1984.

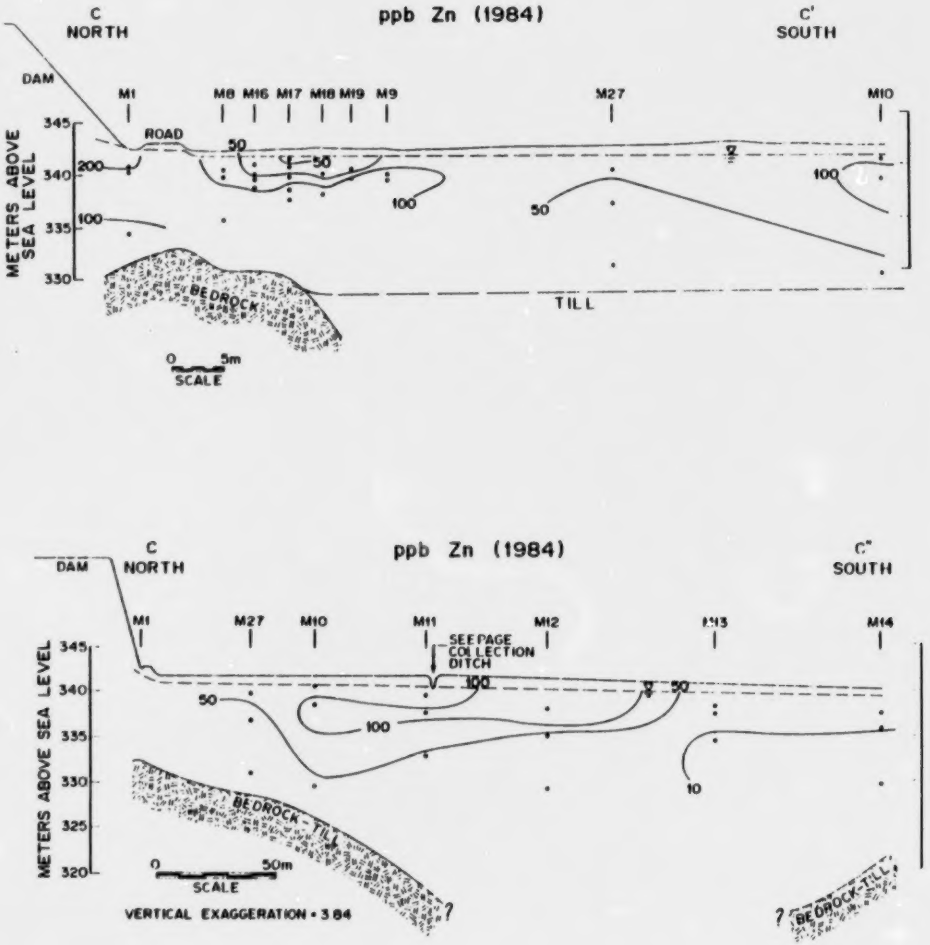


Figure 40. Zn profiles along the Centerplane and Far Centerplane for 1984.

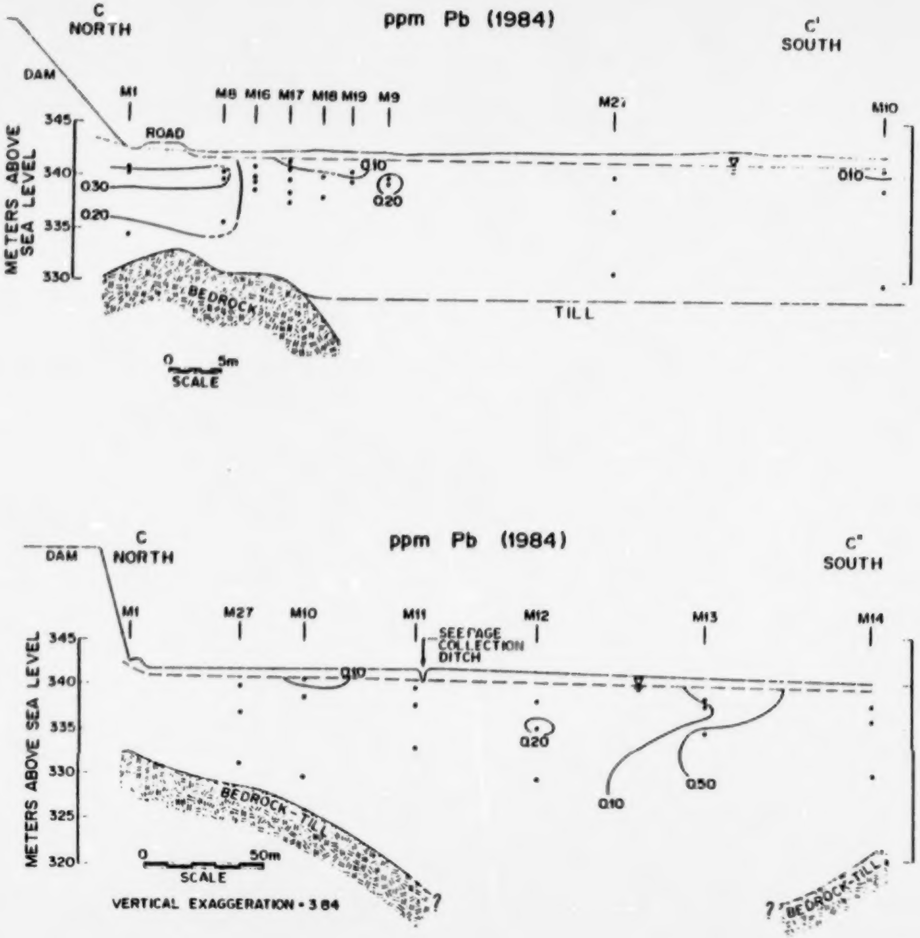


Figure 41. Pb profiles along the Centerplane and Far Centerplane for 1984.

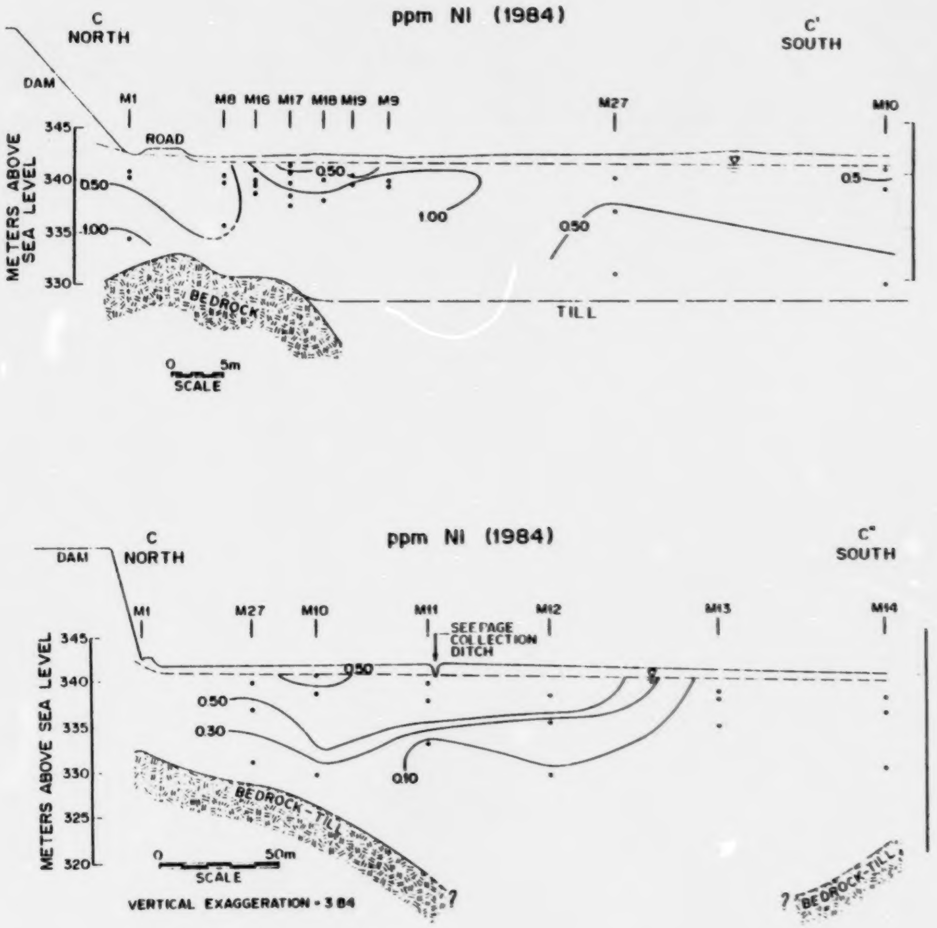


Figure 42. Ni profiles along the Centerplane and Far Centerplane for 1984.

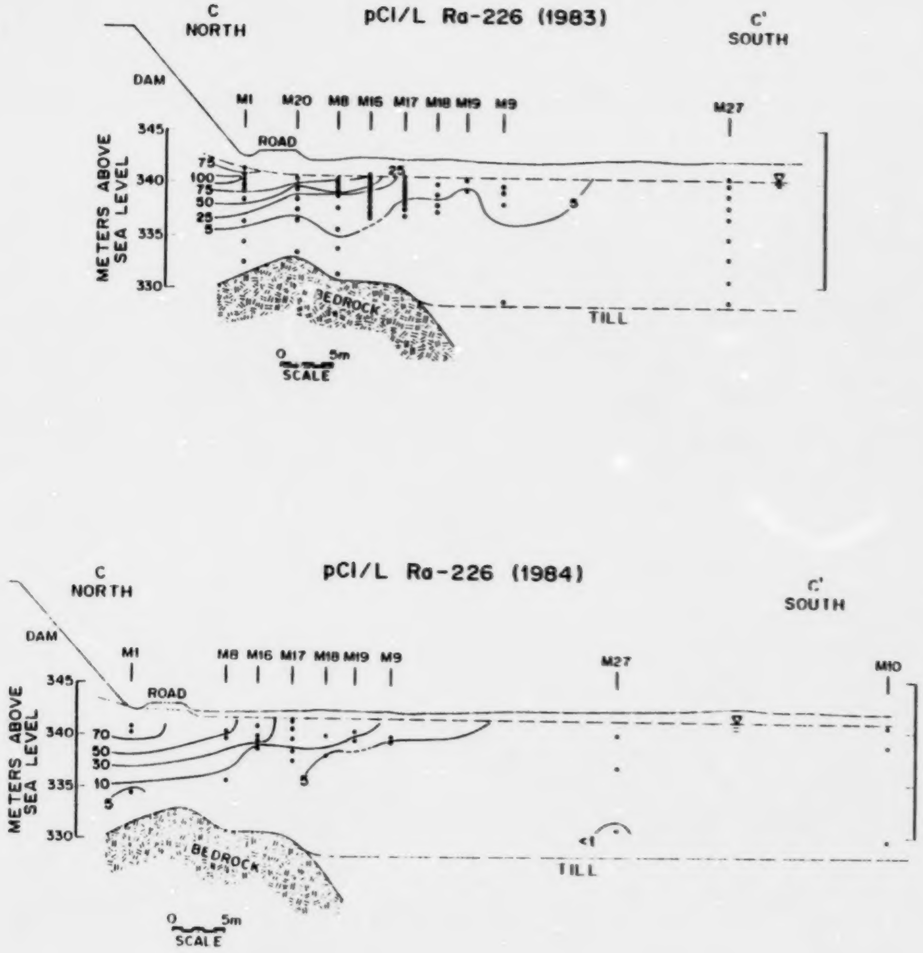


Figure 43. Ra-226 profiles along the Centerplane for 1983 and 1984.

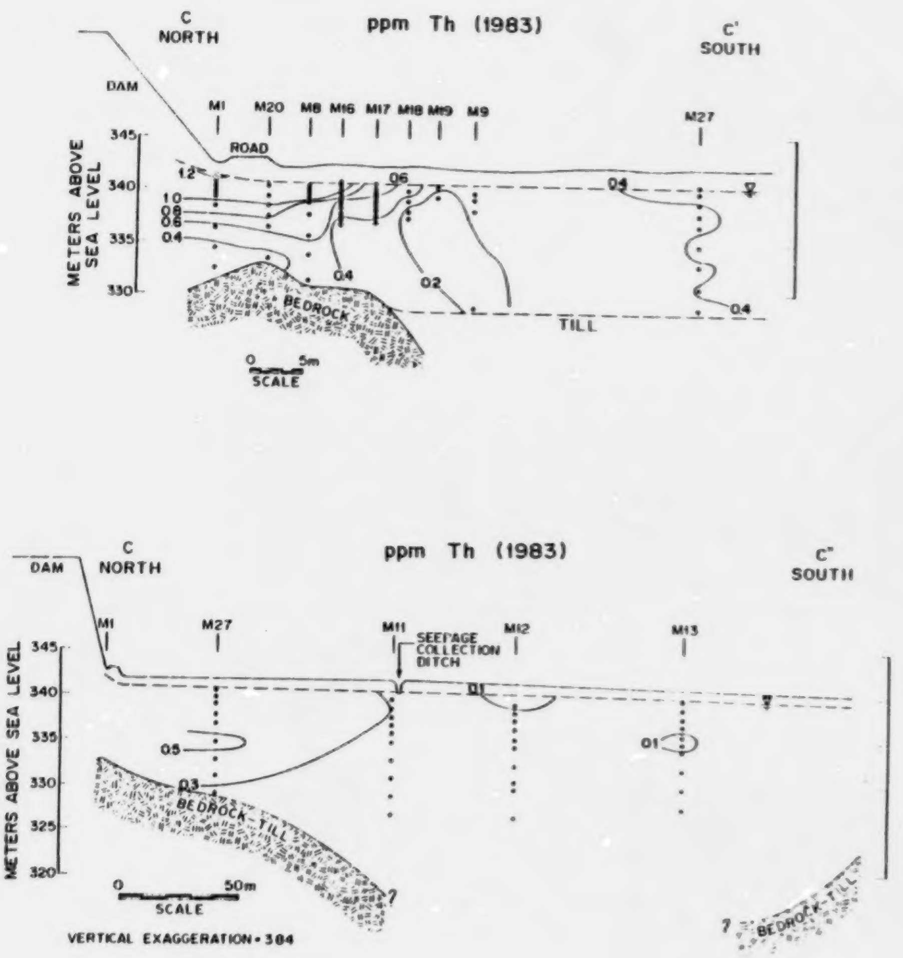


Figure 44. Th profiles along the Centerplane and Far Centerplane for 1983.

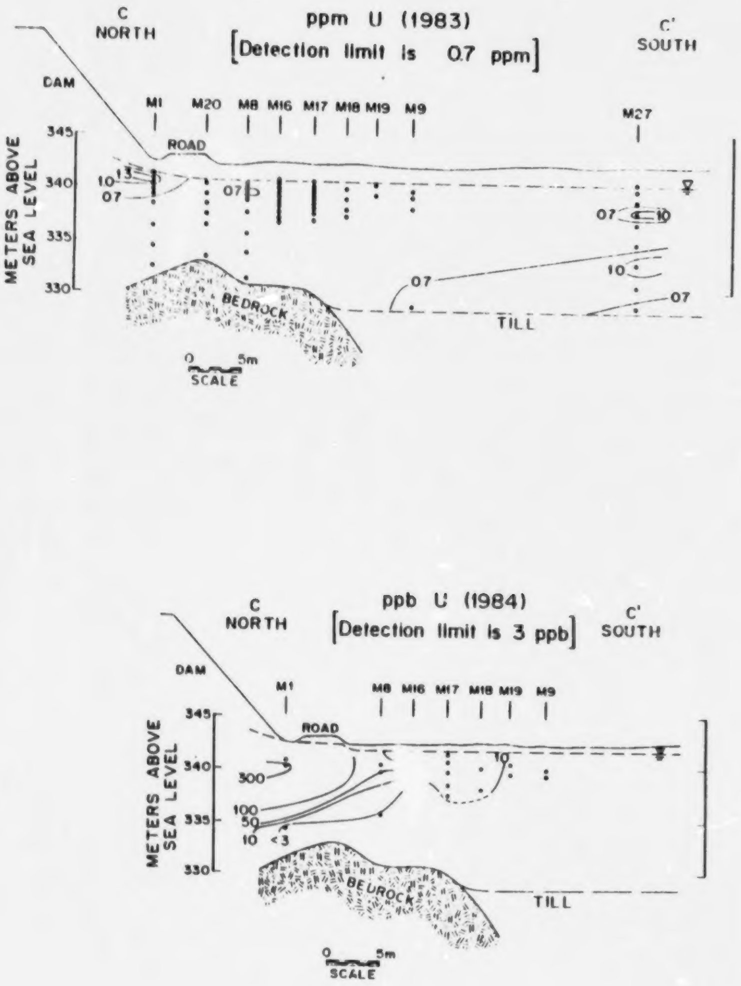


Figure 45. U profiles along the Centerplane for 1983 and 1984.

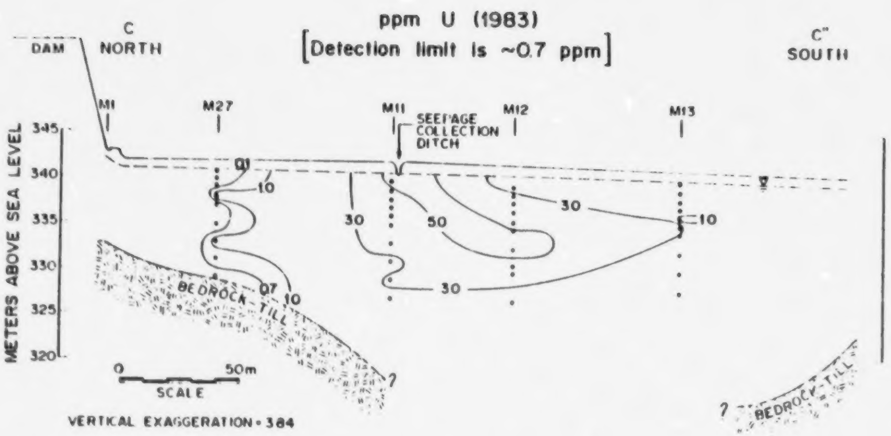


Figure 46. U profile along the Far Centerplane for 1983.

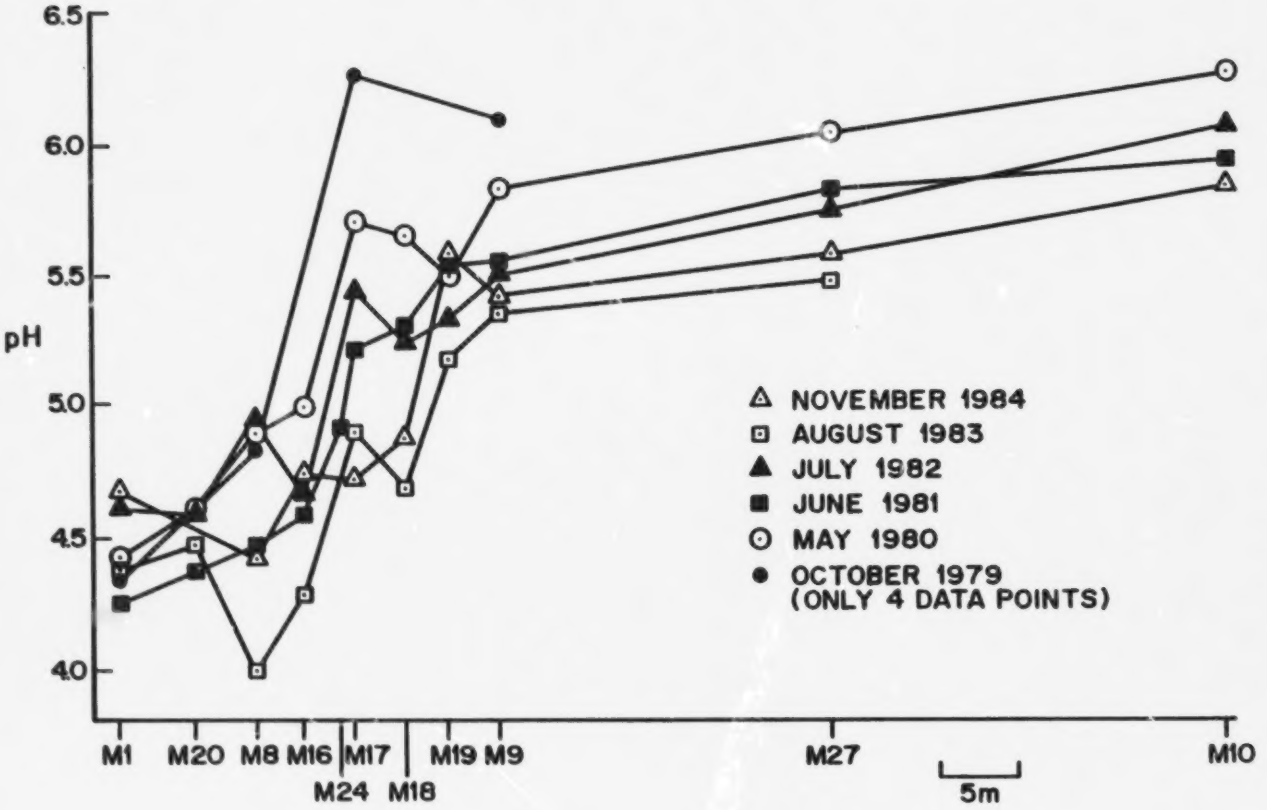


Figure 47. pH profiles along the one-dimensional Centerline for 1979-1984.

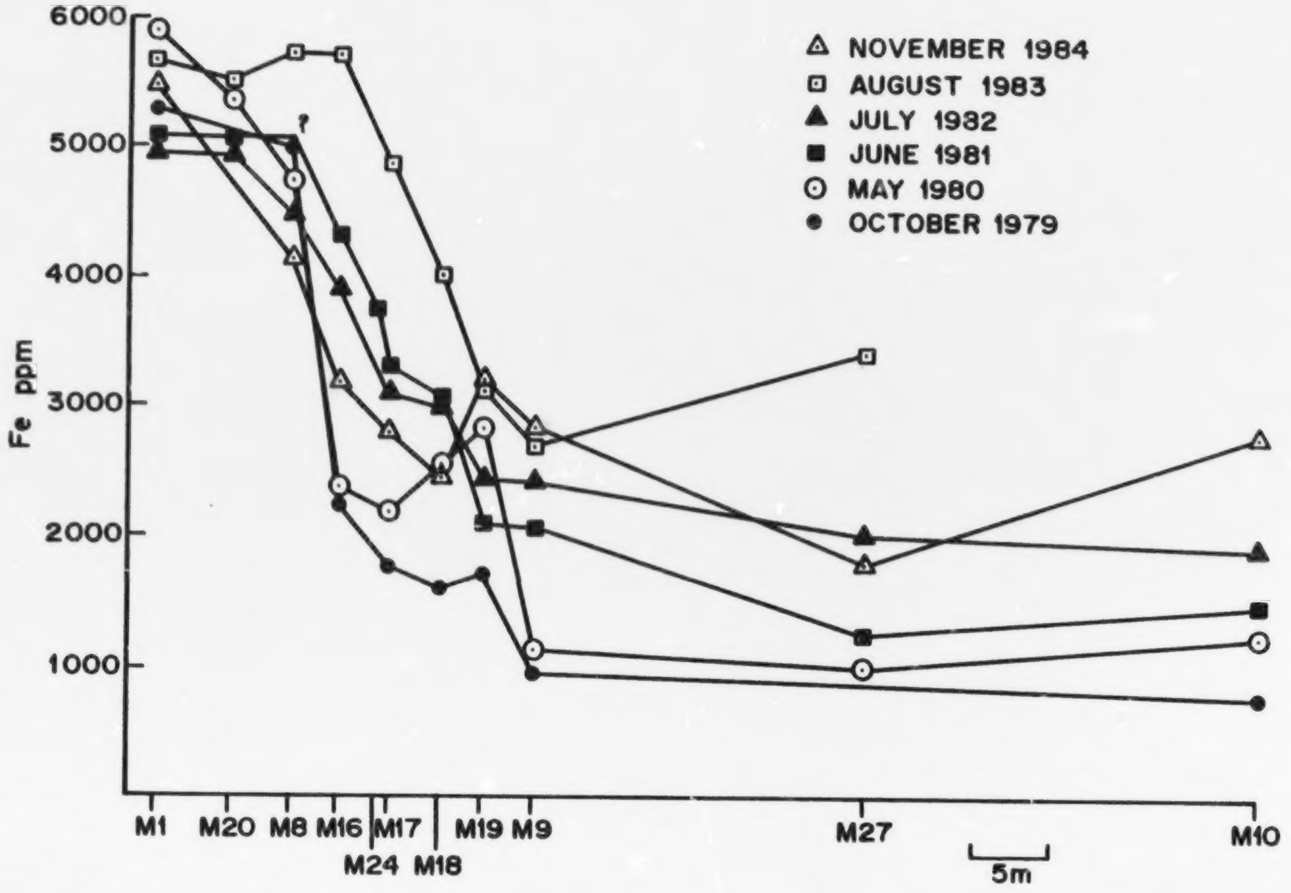


Figure 48. Fe profiles along the Centerline for 1979-1984.

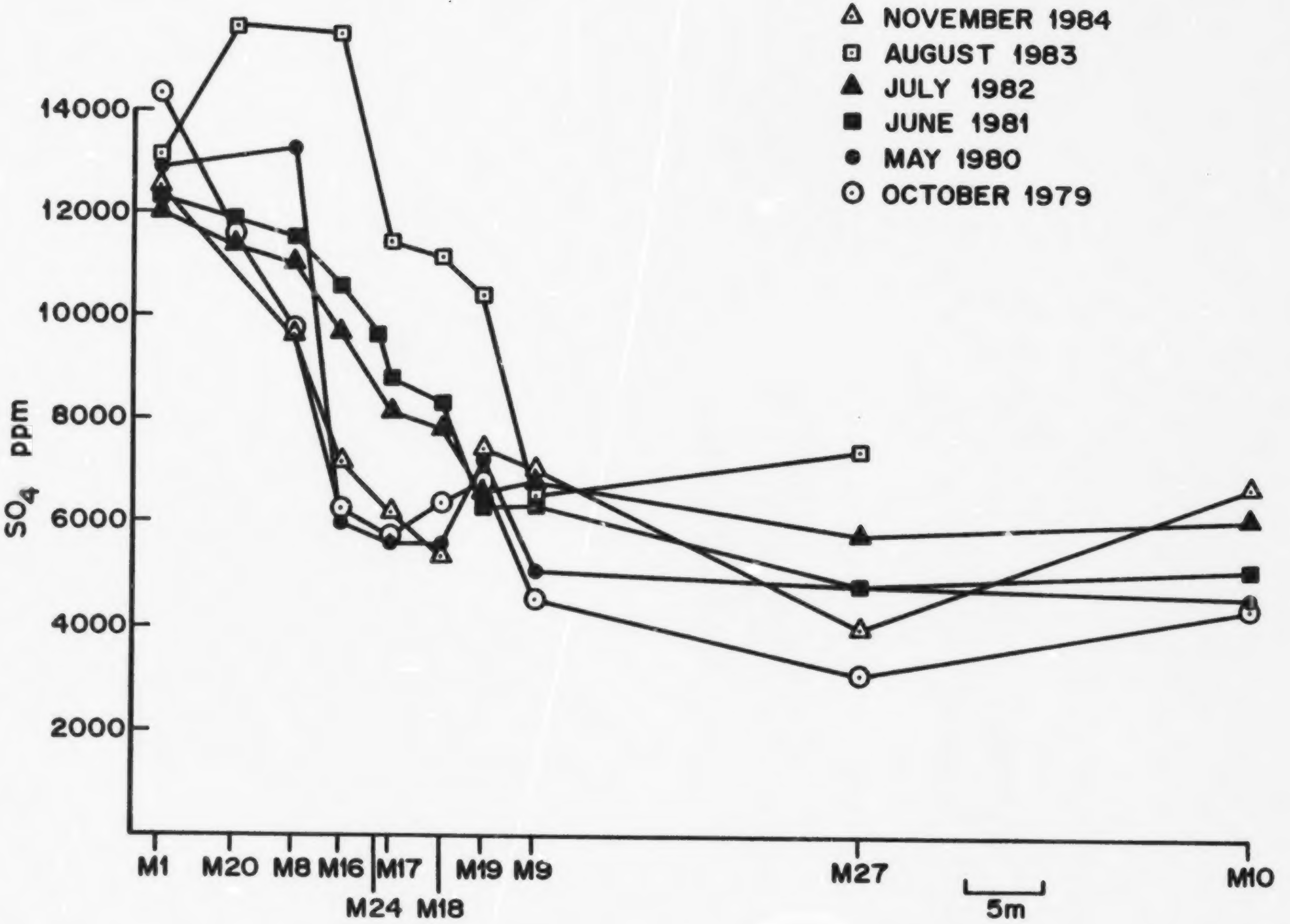


Figure 49. SO_4 profiles along the Centerline for 1979-1984.

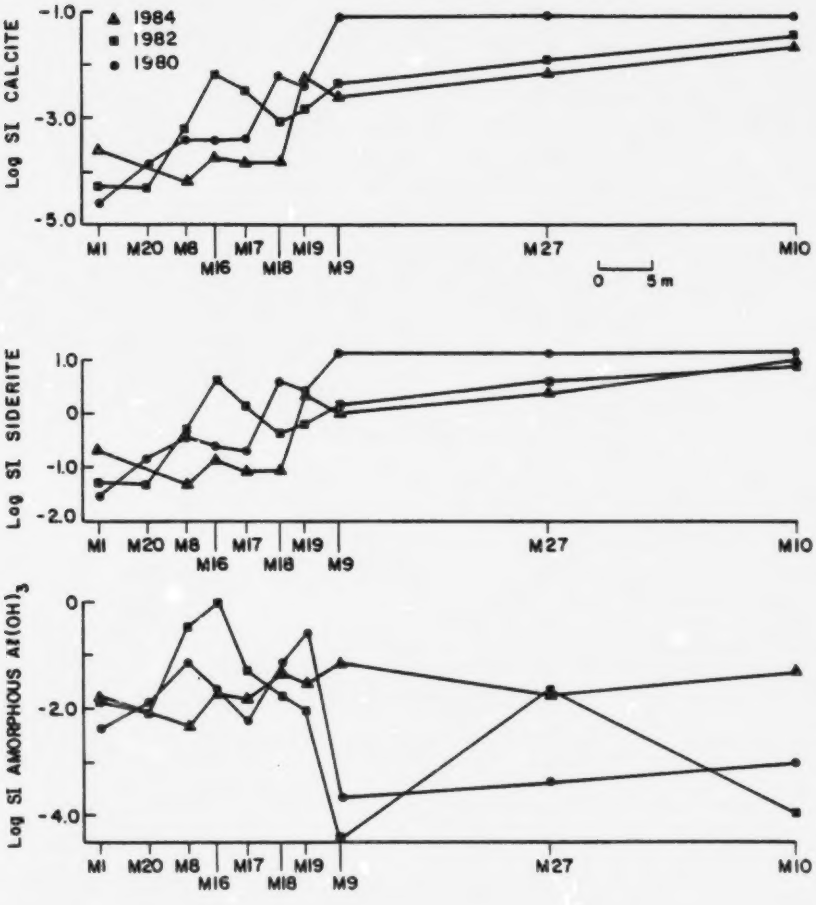


Figure 50. Log SI calcite, siderite, and amorphous Al$(OH)_3$ along the Centerline in 1980, 1982, and 1984.

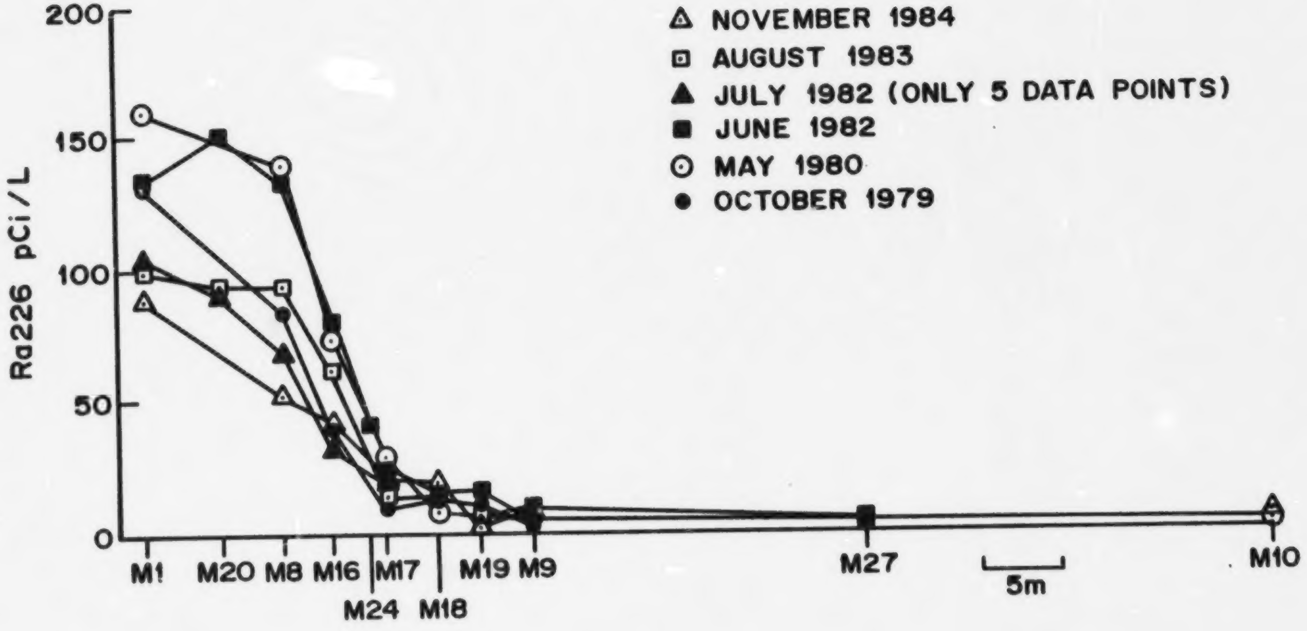


Figure 51. Ra-226 profiles along the Centerline for 1979-1984.

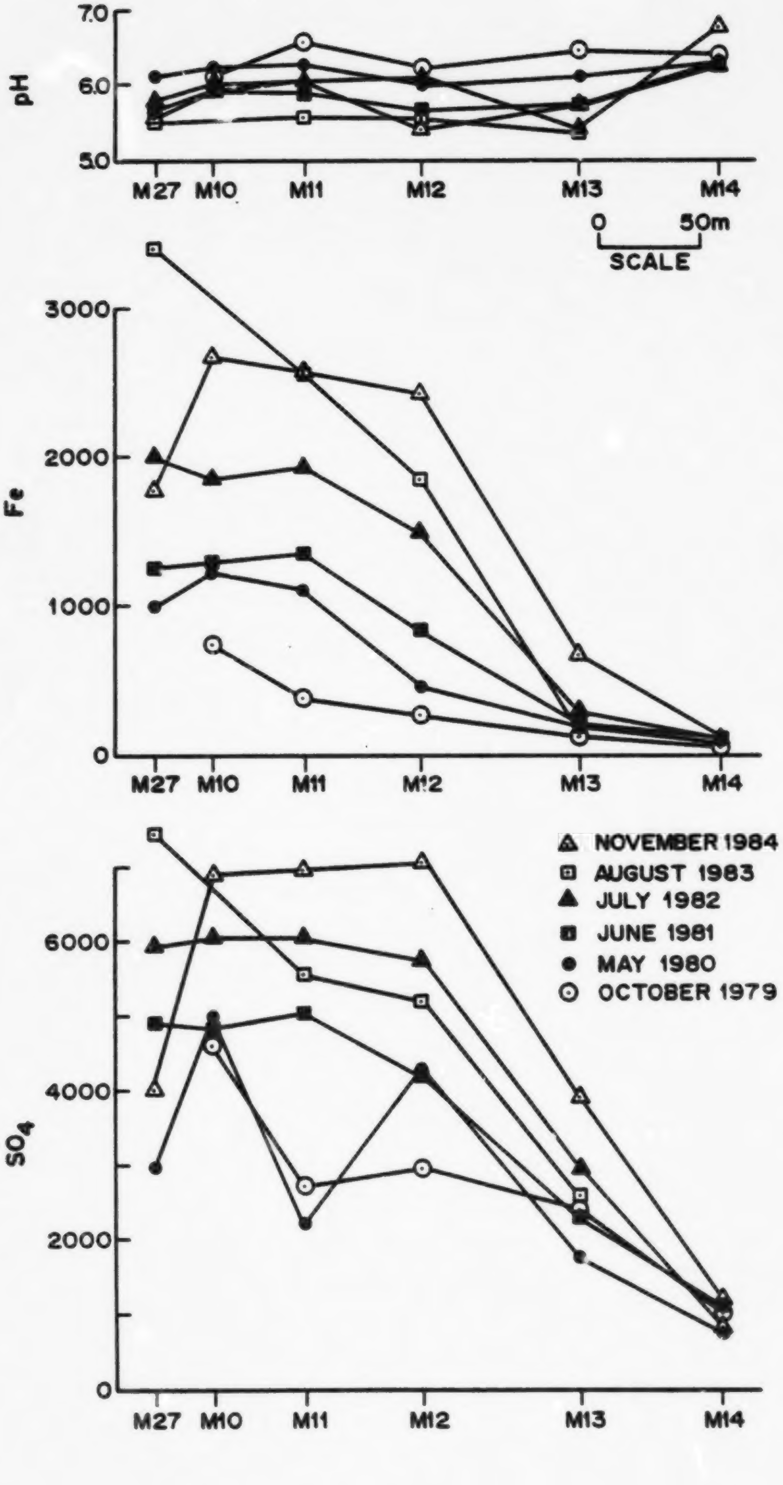


Figure 52. pH, Fe, and SO_4 profiles along the Far Centerline in 1979-1984.

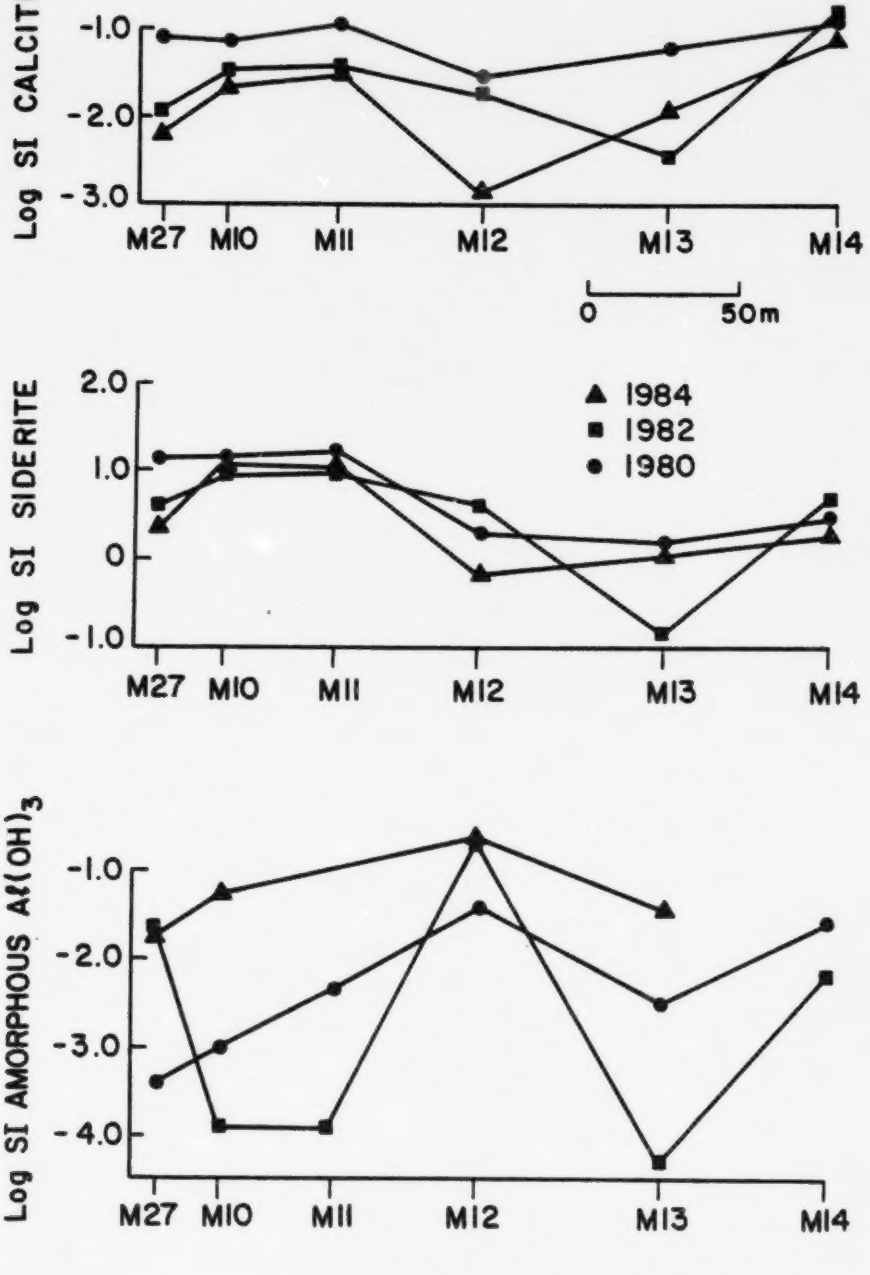


Figure 53. Log SI calcite, siderite, and amorphous $Al(OH)_3$ along the Far Centerline in 1980, 1982, and 1984.

Appendix A

Table A.1
August 1983 and November 1984 pH/conductivity data

1984 conductivities are corrected to 25° C through KCl standards/ 1983 conductivities are corrected to 10°C through KCl standards.

Piez	1983	1984
M1		
Center	5.7/5800	--
1	5.9/6200	6.21/5994
2	5.7/6800	6.02/5708
3	5.8/7200	5.19/5994
4	4.5/7800	4.72/6482
5	4.6/8100	4.71/6610
6	4.4/7600	4.69/6695
7	4.5/7800	4.60/6397
8	4.3/6500	4.65/4506
9	--	4.04/2081
10	--	4.61/5335
M2		
1	--	6.21/5747
2	--	6.25/5630
3	--	6.24/5514
4	--	5.94/5377
5	--	5.62/4929
6	--	5.13/3916
7	--	5.11/3955
8	--	5.25/3507
9	--	5.19/3507
10	--	4.36/1446
11	--	3.82/1438
12	--	5.43/ 890
M3: pipes broken and/or unmarked		
M4: pipes broken and/or unmarked		
M8		
Center	5.8/5700	--
1	5.8/6200	6.11/5282
2	5.6/6800	5.92/5157
3	5.6/6900	5.97/5121
4	5.7/6800	5.89/5139
5	4.7/8200	4.61/5157
6	4.6/8800	4.68/5182
7	4.5/9000	4.58/5318
8	4.0/9100	4.46/5515
9	--	4.52/5461

M9		
Center	5.9/5100	--
1	Missing	
2	Missing	
3	Missing	
4	Missing	
5	5.5/6000	6.09/4645
6	5.4/6200	5.94/4715
7	5.2/6100	5.39/4574
8	Missing	
9	Missing	
10	--	6.64/ 835
11	Missing	
M10		
1	--	6.42/4538
2	--	6.50/4338
3	--	6.75/2940
4	--	6.09/4547
5	--	6.19/4633
6	--	5.91/4566
7	--	5.83/4319
8	--	4.99/ 473
9	--	Dry
M11		
Center	5.8/4700	--
1	6.2/3800	6.63/3611
2	6.1/3700	6.45/4255
3	6.0/3800	6.40/4493
4	5.8/4100	6.25/4688
5	5.7/4300	6.24/4535
6	5.7/4100	6.16/4484
7	5.6/4500	6.01/4493
8	5.9/4500	6.05/4374
9	5.6/4100	5.92/3882
Seepage Collection Ditch		3.43/1890

M12		
Center	6.3/2100	--
1	5.9/4500	6.27/5485
2	5.8/3300	6.39/4457
3	5.8/4800	6.18/5393
4	5.7/4000	6.21/4967
5	5.8/4000	6.24/4858
6	5.6/4100	6.08/4816
7	5.6/4500	5.77/4942
8	5.4/4000	5.40/4917
9	6.1/ 150	4.61/1514
M13		
Center	6.5/1350	--
1	6.3/1500	6.90*/1609
2	6.2/1800	6.65*/2250
3	6.0/2000	6.43*/2187
4	6.3/ 400	6.93*/ 914
5	6.6/ 650	6.79/1138
6	6.2/1800	5.93/4231
7	5.8/2700	5.74/4276
8	5.4/3600	5.71/1013
9	5.6/ 150	6.17/ 514

(* = value adjusted by -0.12, see Section 2.1)

M14		
1	--	6.85/2275
2	--	7.06/1800
3	--	7.01/1756
4	--	7.06/1015
5	--	7.02/1552
6	--	6.37/2166
7	--	6.52/2185
8	--	5.82/ 721
9	--	5.90/ 525
Buckles Creek		6.40/ 116
M16		
Center	5.8/6200	--
5.0	5.7/6100	5.64/5434
4.5	5.5/6700	5.93/5264
4.0	5.6/6900	5.91/5214
3.5	5.5/7200	6.00/5248
3.0	5.0/7100	5.71/5197
2.5	4.6/8300	4.75/4723
2.0	4.4/9500	4.64/4791
1.5	4.3/9800	4.69/4672
1.0	4.4/9700	4.59/4672

M17		
Center	5.4/5800	--
5.0	5.3/6600	5.93/5095
4.5	5.4/6300	5.73/5046
4.0	5.7/6100	5.69/5111
3.5	5.3/6300	5.88/4947
3.0	5.4/6700	5.85/4931
2.5	4.9/7900	4.74/4355
2.0	4.2/8000	4.35/4076
1.5	3.3/8300	4.26/4092
1.0	--	4.11/ 396
M18		
5	5.7/6100	5.92/4600
4	5.8/5900	5.97/4491
3	5.5/7100	5.43/4573
2	4.7/7800	4.92/3902
1	--	5.36/1366
M19		
3	5.4/6100	5.50/5023
2	5.2/7000	5.66/3032
M20		
Center	6.1/6100	--
1	5.9/6100	6.03/5825
2	6.4/6500	6.02/5708
3	5.5/6200	5.96/5786
4	4.9/6900	5.81/5608
5	4.5/8500	5.54/5628
6	--	5.02/3910
7	--	6.05/5608
M21		
1	--	6.29/5338
2	--	6.31/5299
3	--	6.08/5241
4	--	5.73/5066
5	--	5.63/5144
6	--	5.83/5319
7	--	6.17/2942
8	--	6.08/1547
9	--	Dry
M24		
1	--	5.99/4927
2	--	5.97/4819
3	--	5.95/4618
4	--	5.91/4587
5	--	5.34/4510

M25		
1	--	5.95/6353
2	--	6.08/6064
3	--	Tube split
4	--	5.97/6022
5	--	5.94/5857
6	--	5.64/5795
7	--	4.40/4843
8	--	4.39/4863
9	--	4.10/4801
10	--	Dry
M27		
Center	5.8/4800	--
1	6.0/4300	6.48/4907
2	6.2/3400	6.75/3901
3	5.7/5100	Tube split
4	5.8/5200	6.48/4752
5	6.0/4500	6.34/4741
6	5.7/5100	5.67/4774
7	5.2/5800	5.58/3492
8	5.5/5100	6.23/2277
9	--	Dry

Table A.2
August 1983 Water Analyses

All concentrations are in ppm except:
-pH in pH units
-conductivity in uS/cm
-Ra-226 in pCi/L
-Eh in millivolts (N.B.: reported relative to calomel reference)

Suspect analyses of major ions are marked with: (?)

Data were measured by Nand Dave, Tjoe Lim, and Yvonne Boucher of the Elliot Lake Laboratory of CANMET.
Data are reproduced here by their consent.

Piez	M1-M	M1-1	M1-2	M1-3	M1-4	M1-5	M1-6	M1-7	M1-8
Fe	2110	3230	4140	5530	5550	5630	5710	5320	3960
Ca	607	684	537	530	482	545	557	540	552
Mg	411	427	388	395	402	389	371	370	285
Mn	39.2	42.7	43.9	46.2	50.3	48.8	45.5	43.8	36.6
Al	1.23	1.13	1.83	68.0	111.0	112.0	130.0	127.0	101.0
SO4	7302	8485	10321	11975	11873	14144	13097	14059	10365
Si	12.5	14.1	15.7	17.5	17.1	16.6	17.2	17.6	17.2
pH	5.7	5.9	5.7	5.8	4.5	4.6	4.4	4.5	4.3
cond	5800	6200	6800	7200	7800	8100	7600	7800	6500
Eh	+90	+190	+210	+200	+230	+220	+270	+280	+215
Ra-226	4	2	6	52	79	75	100	75	54
Th	0.231	0.343	0.539	0.967	1.077	1.081	1.096	1.123	1.318
U	0.578	0.041	-0.217	-0.085	0.813	0.602	1.298	1.220	0.878

Piez	M8-M	M8-1	M8-2	M8-3	M8-4	M8-5	M8-6	M8-7	M8-8
Fe	2140	3020	3350	4000	4240	5330	5130	5250	5860
Ca	574	590	561	526	612	491	459	508	486
Mg	372	369	322	334	394	387	363	335	366
Mn	36.0	39.1	33.4	36.5	52.5	48.5	50.3	48.8	50.4
Al	0.081	0.190	0.543	0.271	1.28	50.2	61.1	60.3	82.8
SO4	7288	8162	9577	9360	10555	12410	13368	13572	8290
Si	12.7	11.9	11.8	13.2	16.3	16.4	18.8	17.5	19.2
pH	5.8	5.8	5.6	5.6	5.7	4.7	4.6	4.5	4.0
cond	5700	6200	6800	6900	6800	8200	8800	9000	9100
Eh	+280	+270	+190	+320	+280	+290	+300	+320	+160
Ra-226	1	2	6	7	7	61	64	68	94
Th	0.548	0.416	0.634	0.636	0.695	1.193	1.066	1.076	1.395
U	0.386	0.060	0.634	0.154	0.358	0.224	0.836	0.557	0.364

Piez	M9-M	M9-5	M9-6	M9-7	M11-M	M11-1	M11-2	M11-3
Fe	1560	2400	2640	2480	1110	3940(?)	6320(?)	1120
Ca	600	565	559	559	530	550	510	540
Mg	401	396	430	321	330	---	---	437
Mn	38.2	40.3	40.4	36.2	22.6	----	----	34.0
Al	0.50	0.70	0.70	0.80	0.134	0.123	0.301	0.192
SO4	9267	13420	6614	9244	3997.5	2896.4	3502	4530.8
Si	10.6	8.28	6.34	6.11	13.5	12.0	10.7	10.6
pH	5.9	5.5	5.4	5.2	5.8	6.2	6.1	6.0
cond	5100	6000	6200	6100	4700	3800	3700	3800
Eh	-100	-95	-30	-90	+270	+260	+280	+310
Ra-226	2	6	5	6	0	0	0	0
Th	0.173	0.213	0.218	0.349	0.244	0.196	0.218	0.250
U	0.76	0.61	0.22	0.61	2.72	3.06	2.92	3.59

Piez	M11-4	M11-5	M11-6	M11-7	M11-8	M11-9
Fe	2010	2060	2200	2550	2090	1930
Ca	460	440	450	500	450	410
Mg	400	380	352	387	370	304
Mn	41.2	42.8	36.9	33.2	32.8	29.4
Al	0.218	0.235	0.315	0.384	0.310	-----
SO4	5501.5	5514.2	5589.6	5633.0	5646.7	4990.8
Si	18.2	19.9	18.0	18.7	18.5	16.7
pH	5.8	5.7	5.7	5.6	5.9	5.6
cond	4100	4300	4100	4500	4500	4100
Eh	+310	+320	+310	+330	+300	+320
Ra-226	0	0	0	0	0.5	2
Th	0.276	0.281	0.287	0.277	0.303	0.259
U	3.45	3.17	3.41	3.88	4.86	6.20

Piez	M12-M	M12-1	M12-2	M12-3	M12-4	M12-5	M12-6	M12-7	M12-8
Fe	133	1330	500	1730	960	1360	1570	1870	193
Ca	450	507	465	475	543	495	480	380	290
Mg	240	470	337	450	450	488	462	400	280
Mn	15.1	39.5	15.5	43.2	32.2	39.9	42.2	40.0	30.0
Al	0.690	0.140	0.157	2.45(?)	0.135	0.347	0.353	0.762	1.43
SO4	2129.5	4877.0	3238.0	5443.0	4426.1	4638.4	5108.4	5285.6	3435.1
Si	10.8	14.1	9.7	17.2	9.6	12.0	16.0	20.8	27.5
pH	6.3	5.9	5.8	5.8	5.7	5.8	5.6	5.6	5.4
cond	2100	4500	3300	4800	4000	4000	4100	4500	4000
Eh	+300	+290	+300	+300	+300	+300	+330	+310	+310
Ra-226	0	0	0	0	0	0	0	0	0
Th	0.261	0.303	0.302	0.258	0.262	0.257	0.284	0.271	0.242
U	1.50	3.73	3.54	5.65	6.07	2.97	3.61	3.82	3.86

Piez	M12-9	M13-M	M13-1	M13-2	M13-3	M13-4	M13-5	M13-6	M13-7
Fe	8.1	11.7	75.8	171	158	35.5(?)	5207(?)	160	112
Ca	40	245	264	260	291	46.8	834(?)	234	340
Mg	60	70.0	83.0	91.9	124.0	15.0	240	80.4	151
Mn	<1	<1	4.0	3.9	5.0	<1	1.1	4.59	7.5
Al	3.39	9.39	14.4	0.048	0.106	0.123	0.095	0.106	3.51
SO4	110.7	748.1	848.1	1209.3	1387.1	220.9	362.2	1180.0	1832.6
Si	14.4	23.3	50.0	10.5	8.7	8.6	8.2	8.9	8.8
pH	6.1	6.5	6.3	6.2	6.0	6.3	6.6	6.2	5.8
cond	150	1350	1500	1800	2000	400	650	1800	2700
Eh	+210	+250	+240	+220	+260	+210	+210	+240	+260
Ra-226	0	0	0	0	0	0	0	0	0
Th	0.027	0.117	0.157	0.227	0.168	0.057	0.052	0.117	0.172
U	0.023	1.03	1.53	1.66	1.22	3.3	0.755	1.94	1.49

Piez	M13-8	M13-9	M16-M	M16-1.0	M16-1.5	M16-2.0	M16-2.5	M16-3.0
Fe	190	77.0	2920	5700	5820	5780	4900	3680
Ca	431	134	532	483	496	501	554	548
Mg	280	90.0	315	373	394	393	400	330
Mn	15.0	8.6	37.0	46.7	48.7	46.8	50.1	37.0
Al	---	---	0.198	89.1	87.2	81.2	36.9	2.08
SO4	2623.6	973.1	8241	14482	15379	14595	12923	9801
Si	6.5	9.6	10.9	18.8	19.4	19.6	15.6	12.8
pH	5.4	5.6	5.8	4.4	4.3	4.4	4.6	5.0
cond	3600	150	6200	9700	9800	9500	8300	7100
Eh	+290	+270	+230	+240	+260	+250	+330	+290
Ra-226	0.1	0	7	81	62	74	45	9
Th	0.225	0.108	0.214	1.106	1.241	1.149	0.964	0.556
U	2.06	1.31	0.588	-0.063	-0.416	-0.221	0.156	0.162

Piez	M16-3.5	M16-4.0	M16-4.5	M16-5.0	M17-M	M17-5.0	M17-4.5	M17-4.
Fe	3870	3610	3710	2850	2700	2990	2900	3020
Ca	558	549	569	554	481	492	499	528
Mg	345	330	332	315	352	379	338	320
Mn	40.8	36.8	36.3	33.5	23.5	27.7	30.0	30.1
Al	0.298	0.623	0.255	0.633	0.534	0.143	0.572	0.850
SO4	10335	10413	9376	9585	8123	10305	9500	8573
Si	13.3	12.2	13.3	10.9	5.15	4.57	3.75	11.3
pH	5.5	5.6	5.5	5.7	5.4	5.3	5.4	5.7
cond	7200	6900	6700	6100	5800	6600	6300	6100
Eh	+220	+270	+280	+270	-20	-80	-60	+270
Ra-226	6	8	7	8	2	3	5	5
Th	0.483	0.551	0.594	0.337	0.353	0.417	0.425	0.255
U	0.087	0.226	0.356	0.241	-0.08	0.19	0.58	0.672

Piez	M17-3.5	M17-3.0	M17-2.5	M17-2.0	M17-1.5	M18-2	M18-3	M18-4
Fe	3720	3690	4850	4680	4870	3960	3520	2930
Ca	540	534	527	506	494	497	546	544
Mg	349	347	386	377	353	402	332	319
Mn	36.4	40.5	47.2	45.8	37.4	37.8	32.5	26.1
Al	1.74	2.49	18.3	28.7	62.0	12.9	3.00	0.575
SO4	10000	9627	11546	11016	12265	11249	9514	9020
Si	12.3	11.3	16.4	16.5	19.6	6.18	---	10.9
pH	5.3	5.4	4.9	4.2	3.3	4.7	5.5	5.8
cond	6300	6700	7900	8000	8300	7800	7100	5900
Eh	+290	+290	+330	+370	+230	-40	+280	+260
Ra-226	6	8	13	11	11	15	7	3
Th	0.363	0.401	0.687	0.753	0.654	0.540	0.295	0.163
U	0.200	0.169	0.492	0.516	0.28	0.07	0.214	0.119

Piez	M18-5	M19-2	M19-3	M20-M	M20-1	M20-2	M20-3	M20-4
Fe	2820	3130	2910	2530	3290	4000	4010	4640
Ca	544	542	547	650	657	618	635	581
Mg	318	355	366	375	339	355	382	384
Mn	25.4	40.3	34.9	42.5	40.3	46.1	54.6	50.6
Al	0.637	1.00	0.30	0.259	0.288	0.310	0.828	36.7
SO4	8716	10317	8916	10061	10533	18195	19070	10538
Si	11.1	5.00	4.61	13.7	14.2	15.1	15.3	17.5
pH	5.7	5.2	5.4	6.1	5.9	6.4	5.5	4.9
cond	6100	7000	6100	6100	6100	6500	6200	6900
Eh	+270	+30	+30	+70	+140	+150	+300	+270
Ra-226	2	9	4	6	4	9	7	49
Th	0.165	0.208	0.178	0.281	0.626	0.821	1.004	1.516
U	0.066	0.22	0.40	-0.305	-0.432	-0.578	-0.620	0.009

Piez	M20-5	M27-M	M27-1	M27-2	M27-3	M27-4	M27-5
Fe	5490	1080	1300	240(?)	2180	2370	1670
Ca	546	417	667	460	507	404	474
Mg	377	346	381	344	202	166	373
Mn	50.6	30.1	44.1	13.9	43.9	40.2	35.2
Al	101	2.15	-0.223	0.57	-0.30	-0.311	-0.33
SO4	15753	4781	7052	4075	8376	7897	6334
Si	18.8	14.0	11.2	9.80	10.4	7.99	8.14
pH	4.5	5.8	6.0	6.2	5.7	5.8	6.0
cond	8500	4800	4300	3400	5100	5200	4500
Eh	+200	-30	-60	-60	-70	-90	-100
Ra-226	94	2	0	0	0	1	0
Th	1.700	0.283	0.406	0.311	0.523	0.363	0.346
U	0.009	0.66	0.78	1.25	0.54	0.49	1.06

Piez	M27-6	M27-7	M27-8
Fe	2400	2860	3430
Ca	389	469	518
Mg	320	338	373
Mn	37.0	42.6	41.2
Al	0.024	0.70	-0.30
SO4	7240	8222	7490
Si	6.79	5.96	9.59
pH	5.7	5.2	5.5
cond	5100	5800	5100
Eh	+20	+40	-20
Ra-226	2	2	4
Th	0.402	0.464	0.440
U	0.49	0.07	0.00

Table A.3
November 1984 Water Analyses
(See Chapter 2 for details)

All concentrations are in ppm except:
-Field pH in pH units
-Field conductivity in uS/cm
-Ra-226 in pCi/L
(Values are 3% higher than reported by the laboratories because of dilution with HCl. Values are rounded to the same number of significant digits used by the laboratory.)

Alkalinity is expressed as ppm HCO3
Suspect analyses are marked with: (?)
Re-analysis value is marked with: (*)
Replicate analyses on M1-7, M2-2, M14-2, M24-5, M25-7

Codes: PDL = Process Development Laboratory, Rio Algom Limited
GCL = Guelph Chemical Laboratories Limited
(radonuclide analyses by the Chemistry Department of the University of Waterloo)
CAN = Elliot Lake Laboratory of CANMET

Piez	M1-1	M1-6	M1-7	M1-7	M1-7	M1-7	M1-7	M1-7	M1-7
Code	PDL	PDL	PDL	PDL	PDL	GCL	GCL	CAN	CAN
Fe	2915	5447	4918	4963	4975	4780	5530	5150	5084
Ca	639	477	427	407	425	327	311	592.3	535.6
Mg	333	335	306	305	306	144	149	363	365
Na	31	11	11	10	11	4.6	3.8	-	-
K	130	102	95	86	88	47	46	-	-
Mn	19	22	20	20	19	18.2	18.6	41.2	39.6
Al	<0.1	71	82	80	82	72.10	69.01	84.11	84.01
Cu	<0.005	0.022	0.020	0.014	0.034	0.18	0.82	0.039	-
Co	1.8	3.0	3.1	3.0	3.0	4.0	4.0	4.21	4.15
Zn	0.073	0.18	0.22	0.23	0.23	0.29	0.32	-	-
Pb	0.16	0.33	0.28	0.33	0.26	0.9	0.6	0.029	2.05
Ni	0.97	1.6	1.8	1.8	1.8	2.5	2.1	2.110	2.18
SO4	7868	12468	10957	11034	10932	10381	14420	11866	12893
Alk	228.7	29.0	21.4-28.2		<--	<--	<--	<--	<--
SiO2	15	5	1	15	6	47.1	52.7	12.83	13.86
Cl	51.6	15.1	5.5	13.6	14.6	13.6	16.0	56.9	20.6
NH3	50.2	39.8	38.0	33.8	34.3	14.5	13.3	-	-
NO3	-	-	-	-	-	3.0	4.4	-	-
pH	6.21	4.69	4.60	<--	<--	<--	<--	<--	<--
cond	5994	6695	6397	<--	<--	<--	<--	<--	<--
Ra-226	2	79	71	65	79	258.5	281.7	76.29	79.29
Th	<1	<1	<1	<1	<1	-	-	0.0	0.0
U	<0.003	0.332	-	0.367	0.022	-	-	1.054	1.130

Piez	M2-2	M2-2	M2-2	M2-2	M2-2	M2-2	M2-2	M2-6	M2-10
Code	PDL	PDL	PDL	GCL	GCL	CAN	CAN	PDL	PDL
Fe	2338	2303	2315	2343	2156	2333	2359	1463	9.2
Ca	553	520	561	549	267	715.9	659.2	326	193
Mg	318	310	312	317	69	396	381	115	10
Na	39	37	38	36.5	31.8	-	-	5.2	1.1
K	123	115	118	130	122	-	-	38	4.6
Mn	15	15	15	15.3	15.7	31.0	30.8	9	0.41
Al	<0.1	<0.1	<0.1	0.33	0.33	0.248	0.516	6.9	5.9
Cu	0.014	<0.005	<0.005	0.08	0.03	-	0.027	<0.005	0.073
Co	1.0	1.0	1.0	2.4	1.4	1.32	1.28	0.49	0.06
Zn	0.053	0.059	0.055	0.02	0.10	-	-	0.032	0.15
Pb	0.13	0.19	0.20	0.6	0.6	0.805	0.963	0.10	0.06
Ni	0.34	0.36	0.33	0.4	1.1	0.450	0.418	0.24	0.14
SO4	6620	6425	6323	8930	7231	7931	7317	3836	551
Alk	230.5	- 243.1	<--	<--	<--	<--	<--	29.0	-
SiO2	6	5	5	28.2	33.0	18.75	18.03	11	24
Cl	60.0	60.7	60.1	18.5	50.2	90.2	78.7	5.1	<0.42
					*(25.3)				
NH3	53.8	50.5	50.1	34.9	40.5	-	-	17.7	0.19
NO3	-	-	-	3.5	2.3	-	-	-	-
pH	6.25	<--	<--	<--	<--	<--	<--	5.13	4.36
cond	5630	<--	<--	<--	<--	<--	<--	3916	1446
Ra-226	2	2	3	19.63	16.25	0.37	0.0	22	24
Th	<1	<1	<1	-	-	0.0	0.0	<1	<1
U	-	-	-	-	-	<0.8	<0.8	<1	<1

(* = re-analysis)

Piez	M8-2	M8-6	M8-8	M9-6	M9-7	M10-1	M10-6	M10-8
Code	PDL	PDL	PDL	PDL	PDL	PDL	PDL	PDL
Fe	3082	3749	4128	2914	2764	1716	2718	28(?)
Ca	477	419	396	471	429	601	488	56
Mg	260	267	262	262	254	353	289	15
Na	25	14	8.7	24	21	39	27	2.5
K	114	93	77	111	102	111	112	7.2
Mn	13	16	16	14	13	16	15	0.96
Al	<0.1	49	85	<0.1	2.6	<0.1	0.5	1.5
Cu	0.019	0.007	0.014	<0.005	<0.005	<0.005	0.011	<0.005
Co	2.3	2.4	2.6	1.8	2.1	0.71	1.8	0.06
Zn	0.16	0.098	0.085	0.16	0.12	0.036	0.13	0.070
Pb	0.24	0.31	0.31	0.22	0.23	0.14	0.18	0.06
Ni	1.9	1.5	1.8	1.4	1.3	0.20	1.0	0.05
SO4	7579	9099	9718	7308	6959	5924	6943	297
Alk	166.2	29.7	13.3	116.1	50.0	277.5	117.8	6.6
SiO2	8	6	6	8	9	10	12	19
Cl	43.2	23.6	13.6	41.8	36.3	69.2	57.3	1.1
NH3	45.8	34.0	29.1	43.3	39.1	47.5	44.3	2.3
pH	5.92	4.68	4.46	5.94	5.39	6.42	5.91	4.99
cond	5157	5282	5515	4715	4574	4538	4566	473
Ra-226	6	43	55	4	7	2	4	4
Th	<1	<1	<1	<1	<1	-	-	-
U	<0.003	0.05	0.088	<1	<1	-	-	-

Piez	M11-3	M11-7	M11-9	M12-1	M12-5	M12-8	M13-4	M13-7	M13-8
Code	PDL	PDL	PDL	PDL	PDL	PDL	PDL	PDL	PDL
Fe	1670	2608	2067	1728	1837	2470	31(?)	714	436
Ca	577	493	434	564	529	509	132	509	256
Mg	422	291	242	442	427	338	28	378	194
Na	42	30	25	42	38	32	21	43	25
K	122	110	90	124	129	93	1.8	94	65
Mn	32	16	13	32	31	21	1.3	19	11
Al	<0.1	<0.1	0.3	<0.1	<0.1	7.8	<0.1	0.4	<0.1
Cu	<0.005	0.010	<0.005	<0.005	<0.005	0.005	0.005	0.005	0.005
Co	0.57	1.6	1.2	0.84	0.98	2.0	<0.01	0.29	0.25
Zn	0.029	0.10	0.089	0.031	0.047	0.18	<0.002	0.029	0.027
Pb	0.11	0.12	0.15	0.18	0.20	0.14	<0.01	0.12	0.09
Ni	0.07	0.97	0.68	0.07	0.20	0.89	<0.01	0.06	0.04
SO4	6128	6969	5619	6459	6467	7129	441	3913	1205
Alk	196.0	143.6	103.9	184.5	140.0	26.5	112.3	72.6	31.8
SiO2	14	12	28	13	8	23	11	5	8
Cl	72.1	58.1	49.5	75.3	69.8	62.4	35.0	76.0	48.9
NH3	52.1	42.6	36.3	50.1	50.1	41.5	1.2	37.5	24.3
pH	6.40	6.01	5.92	6.27	6.24	5.40	6.93	5.74	5.71
cond	4493	4493	3882	5485	4858	4917	914	4276	1013
Ra-226	2	3	2	2	1	2	1	1	4

*(2172)

(* = re-analysis)

Piez	M14-2	M14-2	M14-2	M14-2	M14-2	M14-2	M14-2	M14-6	M14-8
Code	PDL	PDL	PDL	GCL	GCL	CAN	CAN	PDL	PDL
Fe	62	56	63	61	1856	67.5 *(103)	62.8	102	26
Ca	269	281	281	519	267	333.2	383.7	221	47
Mg	72	72	72	353	64	87.3	85.6	123	25
Na	36	35	35	43.8	31.5	-	-	26	15
K	3.8	3.5	3.6	138	4.0 *(4.1)	-	-	40	16
Mn	4.0	4.0	4.0	3.6	3.6	5.21	5.19	6.1	1.4
Al	<0.1	<0.1	<0.1	0.16	0.13	0.282	0.358	<0.1	<0.1
Cu	0.005	<0.005	<0.005	0.03	0.06	0.011	-	0.005	0.005
Co	0.04	<0.01	<0.01	<0.005	<0.005	<0.3	<0.3	0.11	0.05
Zn	<0.002	0.005	<0.002	0.01	<0.006	-	-	0.010	0.010
Pb	<0.01	<0.01	<0.01	0.3	0.6	0.108	<0.10	<0.01	<0.01
Ni	0.03	<0.01	0.03	0.6	0.008	<0.1	<0.1	0.05	<0.01
SO4	76 *(948)	662	905	1051	608	957.1	955.8	221 *(1254)	209 *(256)
Alk	169.4 - 182.9		<--	<--	<--	<--	<--	106.4	22.9
SiO2	13	7	4	7.6	5.8	17.57	17.39	10	4
Cl	75.2	71.6	73.9	72.0	64.0	152.0	99.7	65.0	34.4
NH3	2.1	1.88	2.18	3.7	4.4	-	-	18.0	6.3
NO3	-	-	-	0.0	0.0	-	-	-	-
pH	7.06	<--	<--	<--	<--	<--	<--	6.37	5.82
cond	1800	<--	<--	<--	<--	<--	<--	2166	721
Ra-226	2	1	2	2.3	3.58	0.0	0.0	3	2
Th	<1	<1	<1	-	-	0.0	0.0	<1	<1
U	<0.003	0.0035	<0.003	-	-	<0.8	<0.8	0.0073	<0.003

(* = re-analysis)

Piez	M16-3.5	M16-2.5	M16-2.0	M16-1.0	M17-5.0	M17-4.0	M17-2.5
Code	PDL	PDL	PDL	PDL	PDL	PDL	PDL
Fe	3225	3236	3236	3005	3006	3098	2753
Ca	470	388	337	341	479	472	330
Mg	257	219	197	188	244	251	188
Na	27	14	7.6	7.1	26	26	12
K	123	86	61	59	118	121	71
Mn	12	12	10	10	11	11	10
Al	<0.1	37	61	59	<0.1	<0.1	26
Cu	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Co	1.4	1.4	1.5	1.3	1.4	1.5	1.1
Zn	0.092	0.059	0.035	0.035	0.14	0.15	0.051
Pb	0.14	0.16	0.13	0.13	0.18	0.18	0.14
Ni	1.2	1.0	1.1	1.0	1.3	1.4	0.74
SO4	7138	7112	7019	6408	7172	7460	6229
Alk	142.8	21.2	17.4	43.4	132.1	93.9	16.8
SiO2	9	10	12	11	11	9	12
Cl	40.4	20.5	10.5	9.3	43.2	42.6	52.3
NH3	42.1	29.6	23.5	21.8	40.5	40.0	25.1
pH	6.00	4.75	4.64	4.59	5.93	5.69	4.74
cond	5248	4723	4791	4672	5095	5111	4355
Ra-226	7	39	34	33	7	8	20
Th	<1	<1	<1	<1	<1	<1	<1
U	<0.003	0.032	0.056	0.046	0.012	0.11	0.014 *(0.45)

(* = re-analysis)

Piez	M17-1.5	M17-1.0	M18-4	M18-2	M19-3	M19-2	M20-2	M20-5
Code	PDL	PDL	PDL	PDL	PDL	PDL	PDL	PDL
Fe	2073	340	2914	2522	3127	1486	3363	3225
Ca	234	52	461	314	475	215	470	475
Mg	130	25	243	173	256	103	256	260
Na	5.7	2.0	25	11	25	5.9	26	26
K	43	4.4	115	67	117	39	125	119
Mn	8.1	2.0	11	9.9	13	6.4	13	14
Al	35	14	<0.1	23	0.7	8.7	<0.1	0.7
Cu	0.005	0.005	<0.005	0.005	<0.005	<0.005	<0.005	<0.005
Co	0.88	0.22	1.2	1.02	2.1	0.51	2.3	1.8
Zn	0.035	0.059	0.14	0.044	0.16	0.02	0.096	0.072
Pb	0.11	<0.01	0.14	0.11	0.14	0.07	0.13	0.12
Ni	0.59	0.09	1.2	0.73	1.8	0.26	2.0	1.2
SO4	4438	654 *(842)	6909	5653	7401	3132	7731	7605
Alk	6.5	-	100.9	10.9	78.2	80.2	139.6	75.5
SiO2	3	39	8	12	9	13	11	9
Cl	6.7	0.68	40.8	52.6	40.2	7.7	41.2	36.8
NH3	15.7	1.8	39.3	23.3	40.5	15.6	43.3	43.1
pH	4.26	4.11	5.97	4.92	5.50	5.66	6.02	5.54
cond	4092	396	4491	3902	5023	3032	5708	5628
Ra-226	12	9	5	15	6	12	8	44
Th	<1	<1	<1	<1	-	<1	<1	<1
U	0.016	0.016	0.011	-	0.093	0.0081 *(0.35)	<0.003	0.078

(* = re-analysis)

Piez	M24-1	M24-4	M24-5	M24-5	M24-5	M24-5	M24-5	M24-5	M24-5
Code	PDL	PDL	PDL	PDL	PDL	GCL	GCL	CAN	CAN
Fe	3018	3074	3259	3213	3201	3562	3187	3275	3255
Ca	513	485	423	411	429	445	439	551.1	508.3
Mg	280	250	245	246	244	231	258	297	304
Na	27	26	22	22	23	16.5	1.80	-	-
								*(16.0)	
K	122	119	98	101	102	108	113	-	-
Mn	14	12	14	15	14	15.1	14.9	31.1	29.9
Al	<0.1	<0.1	4.3	4.5	4.3	4.7	4.5	6.240	6.47
Cu	<0.005	<0.005	0.010	0.010	<0.005	0.03	0.80	-	-
Co	2.0	2.1	1.9	1.9	1.9	2.9	2.9	2.45	2.49
Zn	0.12	0.14	0.093	0.09	0.098	0.08	0.10	-	-
Pb	0.25	0.19	0.15	0.18	0.12	0.3	0.9	1.16	1.1
Ni	1.4	1.9	1.2	1.1	1.1	1.3	1.9	1.34	1.40
SO4	7282	7070	7426	7435	7410	8127	8652	8580	8311
Alk	200.3	164.8	56.3	- 53.0	<--	<--	<--	<--	<--
SiO2	2	5	4	1	1	23.1	27.1	11.52	12.07
Cl	43.6	43.4	32.5	31.5	36.8	11.8	6.7	66.3	58.9
NH3	40.5	39.3	40.8	40.8	41.8	20.3	30.4	-	-
NO3	-	-	-	-	-	3.5	2.1	-	-
pH	5.99	5.91	5.34	<--	<--	<--	<--	<--	<--
cond	4927	4587	4510	<--	<--	<--	<--	<--	<--
Ra-226	4	8	12	13	13	47.7	50.0	16.9	14.5
Th	<1	<1	<1	<1	<1	-	-	0.0	0.0
U	-	-	-	-	-	-	-	<0.8	<0.8

(* = re-analysis)

Piez	M25-2	M25-4	M25-7	M25-7	M25-7	M25-7	M25-7	M25-7	M25-7
Code	PDL	PDL	PDL	PDL	PDL	GCL	GCL	CAN	CAN
Fe	3052	3363	1923	1958	1958	1968	2062	1926	1911
Ca	518	479	320	329	322	431	415	382.6	410.5
Mg	287	257	149	146	149	321	340	173	173
Na	29	26	6.9	6.7	7.1	6.9	5.4	-	-
K	125	123	39	40	40	96	95	-	-
Mn	14	14	8.8	9.4	9.4	8.9	8.9	15.7	15.7
Al	<0.1	<0.1	76	76	77	71.07	67.98	87.84	87.84
Cu	<0.005	<0.005	0.010	<0.005	<0.005	0.06	0.14	0.046	-
Co	1.9	2.2	1.4	1.3	1.4	2.1	2.0	1.66	1.63
Zn	0.060	0.081	0.047	0.045	0.053	0.02	0.07	-	-
Pb	0.14	0.15	0.07	0.13	0.10	0.9	1.2	0.754	0.765
Ni	1.3	1.8	1.2	1.1	1.1	1.5	1.3	1.41	1.44
SO4	7486	7579	4787	4923	4711	4728	4604	5488	5500
Alk	182.5	156.1	7.2 -	9.1	<--	<--	<--	<--	<--
SiO2	8	6	1	8	7	11.0	10.8	29.58	29.79
Cl	46.3	39.2	8.4	10.1	9.8	9.5	8.1	31.3	17.3
NH3	43.8	41.3	17.7	17.5	17.7	13.5	14.1	-	-
NO3	-	-	-	-	-	3.9	2.9	-	-
pH	6.08	5.97	4.40	<--	<--	<--	<--	<--	<--
cond	6064	6022	4843	<--	<--	<--	<--	<--	<--
Ra-226	4	6	24	26	25	78.1	68.88	33.9	38.3
Th	<1	<1	<1	<1	<1	-	-	<1.0	<1.0
U	-	-	-	-	-	-	-	<0.8	<0.8

Piez	M27-1	M27-4	M27-7
Code	PDL	PDL	PDL
Fe	1820	2303	1785
Ca	634	558	326
Mg	361	311	172
Na	41	32	15
K	123	117	72
Mn	18	16	10
Al	<0.1	<0.1	0.3
Cu	<0.005	<0.005	<0.005
Co	0.64	1.2	1.1
Zn	0.027	0.031	0.056
Pb	0.11	0.15	0.11
Ni	0.12	0.43	0.73
SO4	5806	6000	4031
Alk	276.1	233.3	88.8
SiO2	7	16	8
Cl	70.8	57.1	23.6
NH3	60.1	54.5	31.0
pH	6.48	6.48	5.58
cond	4907	4752	3492
Ra-226	<1	1	3
Th	<1	<1	<1